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ANALYSIS OF A NUCLEAR-POWERED LIQUID-METAL DUCTED-FAN CYCLE

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RESEARCH MEMORANDUM

ANALYSIS OF A NUCLEAR-POWERED LIQUID-METAL DUCTED-FAN CYCLE

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By F. E. Rom and W. W. Wachtl

SUMMARY

An analysis of a nuclear-powered liquid-metal ducted-fan cycle is presented for a range of engine operating conditions at flight Mach numbers of 0.9 and 1.5 and at an altitude of 50,000 feet.

The compressor and fan pressure ratios, heat-exchanger inlet Mach number, and duct-outlet temperature are optimized for given heat-exchanger wall temperatures to give maximum thrust per engine-plus-exchanger weight, which in turn results in minimum gross weight.

Airplane gross weight and reactor heat release are presented for a range of the sum of reactor, shield, payload, and auxiliary weight, and for typical values of airplane lift-drag ratio and structure-to-gross weight ratios. For a heat-exchanger effective wall temperature of 1800° R, sum of the shield, reactor, payload, and auxiliary weight of 150,000 pounds, and structure-to-gross weight ratio of 0.35, the airplane gross weight is 288,000 pounds for a flight Mach number of 0.9. The reactor maximum wall temperature is 1858° R. For a flight Mach number of 1.5, the airplane gross weight is 367,000 pounds and the reactor maximum wall temperature is 2080° R for the same assumptions. The effect of altitude on gross weight and reactor heat release is also shown.

The required gross weight and reactor heat release for the ducted-fan cycle is compared with that required for the turbojet cycle. The gross weight for both cycles is approximately the same. The reactor heat releases required for the ducted fan are about 10 and 20 percent higher than for the turbojet cycle for flight Mach numbers of 0.9 and 1.5, respectively.

INTRODUCTION

A general study of nuclear-powered aircraft propulsion cycles is being carried out at the NACA Lewis laboratory. Several reports giving the results of previous studies have been issued. References 1 and 2 discuss the direct-air cycle while reference 3 is a preliminary comparison of the direct-air, liquid-metal turbojet, and helium compressor-jet cycles. Reference 4 presents a detailed [redacted]

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turbojet cycle. The liquid-metal turbine-propeller cycle is analyzed in reference 5. The present report extends these studies by considering the nuclear-powered liquid-metal ducted-fan cycle.

The chemically fueled ducted-fan cycle is studied in reference 6 as a dual-purpose power plant where the cycle showed high-speed design-point performance comparable with that of the turbojet but superior low-speed off-design performance. According to these results, the ducted fan may also have possibilities as a nuclear-powered high-performance engine with good low-speed off-design characteristics. The analysis presented herein considers the high-performance design-point nuclear-powered ducted-fan cycle. In this cycle the shaft power output of a compressor-turbine combination (defined herein as basic engine) powered with a nuclear heat source is used to drive a ducted fan. The duct air is heated by the same nuclear heat source. 2577

Engine performance is emphasized inasmuch as reference 4 indicated that for fixed values of airplane lift-drag ratio, structure-to-gross-weight ratio, and the sum of shield, reactor, payload, and auxiliary weights, the maximum engine net thrust per pound of engine-plus-exchanger weight gives the minimum-gross-weight airplane. However, the engine data are presented in such a manner that the gross weight, reactor heat release, and reactor wall temperature can readily be found.

The results are presented for flight Mach numbers of 0.9 to 1.5 at an altitude of 50,000 feet. The effect of flight altitude on optimum engine design-point airplane performance is also shown. The engine parameters considered are turbine-inlet temperature, basic-engine heat-exchanger effective wall temperature, basic-engine compressor pressure ratio, fan pressure ratio, duct heat-exchanger inlet Mach number, duct heat-exchanger effective wall temperature, and duct-outlet air temperature. The fan pressure ratio, basic-engine compressor pressure ratio, duct heat-exchanger inlet Mach number, and duct-outlet air temperature are optimized for maximum thrust per engine-plus-heat-exchanger weight for a range of duct heat-exchanger effective wall temperatures. In general, a fixed value is assumed for the basic-engine heat-exchanger inlet Mach number and for the effective wall temperature. The effect of changing the basic-engine heat-exchanger effective wall temperature is investigated by considering the case where the basic-engine heat-exchanger effective wall temperature is equal to the variable duct heat-exchanger effective wall temperatures.

The liquid-metal ducted-fan cycle is compared with the liquid-metal turbojet cycle for compatible assumptions to show the relative design-point performances of the two cycles.

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
C_V	velocity coefficient
c_p	specific heat at constant pressure, Btu/(lb)-($^{\circ}$F)
D	drag, lb
d	hydraulic diameter, ft
F	thrust, lb
f	free flow factor (flow area divided by total area)
g	acceleration of gravity, 32.2 ft/sec^2
h	enthalpy, Btu/lb
J	mechanical equivalent of heat, 778 ft-lb/Btu
k	thermal conductivity, (Btu)(ft)/(sec)(sq ft)($^{\circ}$F)
L	lift, lb
l	length, ft
M	Mach number
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
Q	reactor heat release, Btu/sec
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
U	over-all heat transfer coefficient, Btu/(sec)(sq ft)($^{\circ}$F)
V	velocity, ft/sec
W	weight, lb
w	air flow, lb/sec

γ	ratio of specific heats
Δh	enthalpy change, Btu/lb
ΔT_y	difference between local reactor wall and local coolant temperature, $^{\circ}R$
ΔT_z	difference between basic-engine heat-exchanger effective wall and maximum coolant temperature, $^{\circ}F$
δ	ratio of total pressure to NACA standard sea level pressure
θ	ratio of total temperature to NACA standard sea level temperature
ρ	density, lb/cu ft

Subscripts

a	total air flow
c	compressor
d	duct
e	basic engine
F	frontal
f	fan
g	gross
j	jet
K	sum of reactor, shield, payload, and auxiliary
l	liquid
m	reactor maximum wall
N	nacelle
n	net (jet minus inlet momentum)
r	reactor
s	structure

T sum of compressor, turbine, shell, fan, basic-engine heat exchanger, and duct heat exchanger

t turbine

w basic-engine heat-exchanger effective wall

w' duct heat-exchanger effective wall

x heat exchanger

0 free stream

1 fan inlet

2 fan outlet or compressor inlet

2' duct heat-exchanger inlet

3 compressor outlet

3' duct heat-exchanger outlet

4 turbine inlet

5 turbine outlet

DESCRIPTION OF CYCLE

The liquid-metal ducted-fan cycle is shown schematically in figure 1. The engine consists of a compressor-turbine combination (referred to as the basic engine) which drives a ducted low-pressure-ratio compressor (fan). The air leaving the fan is divided between the basic engine and the duct portion of the cycle so as to utilize completely the shaft power of the basic engine. Lithium is used to tranport the heat from the reactor to the basic-engine and duct heat exchangers. The propulsive thrust is supplied by the exhaust jets issuing from the nozzle of both the basic engine and the duct. The stations used in the analysis of the cycle are also shown in figure 1.

ASSUMPTIONS

Engine component efficiencies. - The engine component efficiencies assumed for the analysis are as follows:

Compressor small-stage efficiency	0.88
Fan small-stage efficiency	0.88
Turbine small-stage efficiency	0.88
Exhaust-nozzle velocity coefficient (full expansion)	0.97

The inlet-diffuser total-pressure-recovery ratios P_1/P_0, which are the same as used in reference 4, are 0.965 and 0.950 at Mach numbers of 0.9 and 1.5, respectively.

Tail-pipe pressure ratio P_5/p_0. - In computations of the shaft work 2577
and jet thrust of the basic engine, the basic-engine P_5/p_0 is assumed to be equal to the ram pressure ratio P_1/p_0. According to reference 7 this assumption gives close to the optimum division of power between the jet and propeller for a turbine-propeller engine. Inasmuch as the ducted-fan engine has a lower propulsive efficiency than the turbine-propeller because of its lower air flow, the optimum P_5/p_0 is expected to be slightly higher than for the turbine-propeller. In reference 7, however, it is shown that total thrust is not sensitive to P_5/p_0 on either side of the optimum for the turbine-propeller cycle. Preliminary calculations on the ducted-fan cycle indicated the same small effect. Consequently the assumption that P_5/p_0 is equal to P_1/p_0 is considered applicable to the ducted fan. Both the duct and basic-engine exhaust jets are assumed to discharge to atmospheric static pressure.

Engine weight. - The weight of the ducted-fan engine exclusive of the heat exchangers was calculated by adding the weights of the fan, compressor, shell, and turbine. The relations used to compute the component weights are extrapolated from the best current values. The weights of the fan, compressor, and turbine, including gears, shafting, and casing are assumed to vary directly with the corresponding corrected inlet air flow of each component (hence, inlet area) and directly with the logarithm of the pressure ratio (hence, number of stages of equal weight) of each component. The shell weight, consisting of the engine inlet, duct, and nozzle, is based on a steel shell having a thickness of 0.05 inch. In the range of fan pressure ratios considered, the 0.05-inch thickness is sufficiently strong to withstand the pressure differentials to which it is exposed. Additional assumptions made to facilitate calculation of the shell weight are: (1) the diameter is constant for the entire engine length, as determined by the sum of the heat-exchanger frontal areas; (2) the length-to-diameter ratio is 4; and (3) the heat-exchanger free-flow ratios are as assigned.

Heat exchanger. - The liquid-metal-to-air heat exchangers are assumed to be of the tubular counterflow type with air flowing through the tubes. The tubes are assumed to be of stainless steel with 0.25-inch internal diameter, 0.01-inch wall thickness, and the heat-exchanger free-flow factor A_a/A_f is 0.65. The weight of the heat exchanger includes the shell, baffles, headers, and coolant which fills the space surrounding the tubes.

The heat-exchangers are assumed to have constant effective wall temperatures T_w and T_w' in order to simplify heat-transfer calculations. The heat-exchanger length-to-diameter ratio l/d and pressure drop are computed from this assumption by means of the charts presented in reference 4, which were obtained by the methods given in reference 8. Reference 8 calculates pressure drop by a step-by-step process which takes into account simultaneous friction and momentum pressure drop. No error in l/d and only a slight error in pressure drop results from assuming a constant effective wall temperature.

Reactor maximum wall temperature T_m. - The reactor maximum wall temperature is calculated from the following assumptions:

1. The flow leaving the reactor is divided into two parallel flows, one to each heat exchanger.

2. The power input along the reactor passage is constant.

3. The basic-engine heat-exchanger inlet liquid-metal temperature is 50° F higher than T_w for a reactor heat release Q of 100,000 Btu per second and this difference is directly proportional to the reactor heat release.

4. The liquid-metal (lithium) velocity in the reactor is 15 feet per second.

5. The reactor diameter and length are each 2.5 feet.

6. The reactor free-flow ratio is 0.35.

7. The hydraulic diameter of the reactor flow passages is 0.25 inch.

8. The heat generated by the reactor is only that required to power the engines with no auxiliaries or heat losses.

Reactor, shield, payload, and auxiliary weights W_K. - A range of values from 100,000 to 200,000 pounds is assumed for W_K, the sum of the reactor, shield, payload, and auxiliary weight (pumps, piping, electrical equipment, etc).

Airplane assumptions. - The structure-to-gross-weight ratio W_s/W_g of the airplane is assumed to be 0.35 and 0.25. The airplane design lift-drag ratio L/D for a submerged engine installation is assumed to be 18 for a flight Mach number of 0.9 and 6 and 9 for a flight Mach number of 1.5.

METHODS

It was shown in reference 4 that optimizing the engine net thrust per engine-plus-exchanger weight F_n/W_T is sufficient to determine the airplane minimum gross weight for fixed values of L/D, W_s/W_g, and W_K.

In the present analysis, a similar optimization for maximum F_n/W_T is carried out.

Cycle Analysis 2577

Range of variables. - The performance of the ducted-fan cycle with a nuclear heat source is calculated at flight Mach numbers M_0 of 0.9 and 1.5 for an altitude of 50,000 feet. The fan pressure ratio P_2/P_1 is varied from 1.2 to 5.0 and the compressor pressure ratio P_3/P_2 is varied from 1.0 to 10.0. In general, T_w is fixed at 2270° R and the turbine-inlet temperature T_4 is fixed at 2000° R. However, a special case is considered where T_w is set equal to T_w' to find the effect of lower-temperature operation; T_w' is varied from 1600 to 2200° R while T_3' is varied from 1100 to 2000° R. The M_2' is varied from 0.12 to 0.24 while the M_3 is held constant at 0.15 based on the results of the turbojet cycle of reference 4 which gave 0.15 as close to the optimum value. In the course of the analysis it was found that a basic engine with $M_3 = 0.12$ gave slightly better engine performance. Therefore this value was used for the case of reduced T_w.

Calculation of net thrust per pound of air per second F_n/w_a. - The fan inlet total temperature T_1 and the total pressure P_1 are determined for the assumed flight conditions and corresponding diffuser-pressure-recovery ratio P_1/P_0. The enthalpy of the air entering the fan h_1 and the enthalpy rise through the fan Δh_f and through the compressor Δh_c are determined from the thermodynamic-property tables and methods presented in reference 9 for the assumed compression efficiencies. The fan-outlet total temperature T_2 and total pressure P_2 are the same as the duct heat-exchanger inlet temperature T_2' and pressure P_2', respectively. Similarly, the compressor-outlet temperature T_3 and pressure P_3 are the same as the basic-engine heat-exchanger inlet temperature and pressure. The heat-exchanger pressure ratios P_2'/P_3' and P_3/P_4 can then be computed from the assumed inlet Mach numbers, effective wall temperatures, and duct-outlet and turbine-inlet temperature from the figures presented in reference 4.

The turbine pressure ratio can be found as follows (assuming that $P_1 = P_5$):

$$\frac{P_4}{P_5} = \frac{P_4}{P_3}\frac{P_3}{P_2}\frac{P_2}{P_1}$$

By use of the thermodynamic charts in reference 9, P_4/P_5, T_4, h_5, and T_5 can be found. The turbine enthalpy drop Δh_t is then determined.

The work available to the fan $w_a \Delta h_f$ is equal to the turbine work $w_e \Delta h_t$ minus the compressor work $w_e \Delta h_c$ as follows:

$$w_a \Delta h_f = w_e \Delta h_t - w_e \Delta h_c \tag{1}$$

The ratio of engine air flow to total air flow is then:

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$$\frac{w_e}{w_a} = \frac{\Delta h_f}{\Delta h_t - \Delta h_c} \tag{2}$$

The basic-engine tail-pipe pressure ratio P_5/p_0, which is equal to P_1/p_0, and T_5 give the basic-engine jet thrust per pound of total air flow from the following equation:

$$\left(\frac{F_j}{w}\right)_e = C_v \sqrt{\frac{2Jc_pT_5}{g}\left[1 - \left(\frac{p_0}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{3}$$

The duct tail-pipe pressure ratio is found as follows:

$$\frac{P_3'}{p_0} = \frac{P_3'}{P_2'}\frac{P_2}{P_1}\frac{P_1}{P_0}\frac{P_0}{p_0} \tag{4}$$

The duct jet thrust per pound of total air flow is then

$$\left(\frac{F_j}{w}\right)_d = C_v \sqrt{\frac{2Jc_pT_3'}{g}\left[1 - \left(\frac{p_0}{P_3'}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{5}$$

The over-all net thrust per pound of total air flow is

$$\frac{F_n}{w_a} = \left(\frac{F_j}{w}\right)_e \frac{w_e}{w_a} + \left(\frac{F_j}{w}\right)_d \left(1 - \frac{w_e}{w_a}\right) - \frac{V_0}{g} \tag{6}$$

Engine-plus-heat-exchanger weight. - The weights of the engine components per pound of total air flow were found by use of the following equations obtained from the assumptions listed in the assumptions section:

$$\frac{W_f}{w_a} = 5.0 \frac{\sqrt{\theta_1}}{\delta_1} \log \frac{P_2}{P_1} \qquad \text{(fan)} \tag{7}$$

$$\frac{W_c}{w_e} = 5.0 \frac{\sqrt{\theta_2}}{\delta_2} \log \frac{P_3}{P_2} \qquad \text{(compressor)} \qquad (8)$$

$$\frac{W_t}{w_e} = 14.1 \frac{\sqrt{\theta_4}}{\delta_4} \log \frac{P_4}{P_5} \qquad \text{(turbine)} \qquad (9)$$

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$$\frac{W_d}{w_a} = 50 \left[\left(\frac{A}{w}\right)_{x,d} \left(1 - \frac{w_e}{w_a}\right) + \left(\frac{A}{w}\right)_{x,e} \left(\frac{w_e}{w_a}\right)\right] \text{(shell)} \qquad (10)$$

The duct heat-exchanger weight per pound of duct air flow $W_{x,d}/w_d$ is found by the following relation derived from the assumptions as in reference 4:

$$\frac{W_{x,d}}{w_d} = 1.9 \ (A/w)_{x,d} \ (l/d)_{x,d} \qquad (11)$$

where $w_d = w_a - w_e$, and $(w/A)_{x,d}$ is the air flow per unit area in the tubes of the duct heat exchanger and is found from P_2', T_2', and M_2'. The duct heat exchanger l/d is found by the methods presented in reference 4.

The basic-engine heat-exchanger weight per pound of basic-engine air flow $W_{x,e}/w_e$ is found similarly by:

$$\frac{W_{x,e}}{w_e} = 1.9 \ (A/w)_{x,e} \ (l/d)_{x,e} \qquad (12)$$

where $(w/A)_{x,e}$ is the air flow per unit area in the tubes of the basic engine heat-exchanger as found from P_3, T_3, and M_3. The heat-exchanger l/d is found by the methods of reference 4.

The total engine-plus-heat-exchanger weight per pound of total air flow W_T/w_a from equations (7) to (12) is then:

$$\frac{W_T}{w_a} = \frac{W_f}{w_a} + \frac{W_d}{w_a} + \frac{W_{x,d}}{w_d}\left(1 - \frac{w_e}{w_a}\right) + \frac{w_e}{w_a}\left(\frac{W_c}{w_e} + \frac{W_t}{w_e} + \frac{W_{x,e}}{w_e}\right) \qquad (13)$$

Net thrust per pound of engine-plus-exchanger weight F_n/W_T. - The value of F_n/W_T is found by dividing F_n/w_a by W_T/w_a (equation (13)):

$$\frac{F_n}{W_T} = \frac{F_n/w_a}{W_T/w_a} \tag{14}$$

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Heat input. - The heat input to the ducted-fan cycle consists of the sum of the heat added to the basic engine and the heat added to the duct.

$$Q = w_d\,(h_3' - h_2') + w_e\,(h_4 - h_3) \tag{15}$$

Dividing by w_a and since $w_d = w_a - w_e$

$$\frac{Q}{w_a} = \left(1 - \frac{w_e}{w_a}\right)(h_3' - h_2') + \frac{w_e}{w_a}\,(h_4 - h_3) \tag{16}$$

Airplane Calculations

Up to this point in the analysis, the methods for obtaining engine performance in terms of F_n/w_a, F_n/W_T, and Q/w_a have been outlined. In order to obtain airplane performance, values must be assigned for L/D, W_s/W_g, and W_K.

Gross weight W_g. - The gross weight of a nuclear-powered airplane is determined by W_K, W_s/W_g, L/D, and F_n/W_T as shown by the following equation taken from reference 4:

$$W_g = \frac{W_K}{1 - \frac{W_s}{W_g} - \frac{1}{\frac{F_n}{W_T}\,\frac{L}{D}}} \tag{17}$$

This equation has been plotted (fig. 2) in convenient form for values of W_s/W_g equal to 0.35 and 0.25 and for a range of over-all airplane L/D. The gross weight factor W_g/W_K is determined directly from F_n/W_T and L/D by use of figure 2; W_g is then found by multiplying W_g/W_K by the desired value of W_K.

Air flow w_a. - The total engine air flow required to fly the airplane is determined from W_g, L/D, and F_n/w_a by the following relation:

$$w_a = \frac{W_g}{\frac{L}{D}\frac{F_n}{w_a}} \tag{18}$$

Reactor Calculations

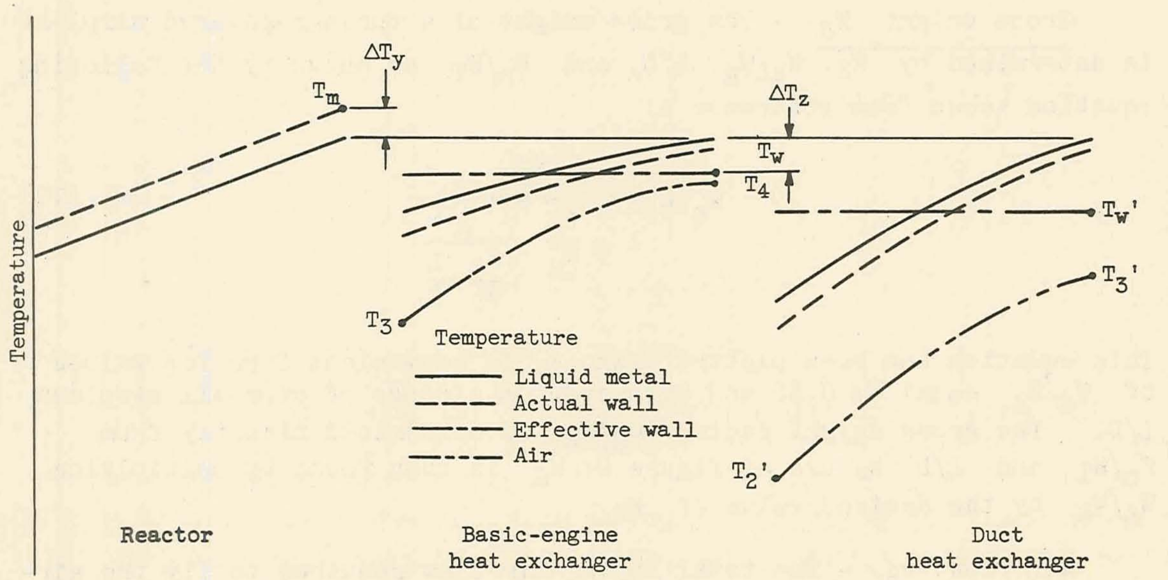
Reactor heat release Q. - The reactor heat release Q expressed in Btu per second is obtained by multiplying Q/w_a (equation (16)) by w_a (equation (18)):

$$Q = \frac{Q}{w_a} w_a \tag{19}$$

The Q calculated in this manner includes only the heat required to power the cycle; no losses or power to drive auxiliary equipment are included.

Reactor maximum wall temperature T_m. - The temperature T_m is obtained by adding the difference between the reactor wall and liquid-metal temperature ΔT_y and ΔT_z (the difference between T_w and maximum liquid-metal temperature) to T_w.

$$T_m = T_w + \Delta T_z + \Delta T_y \tag{20}$$



A heat balance for the two heat exchangers and the reactor will give the desired value of ΔT_z; however, to simplify the calculations, ΔT_z is assumed to be 50° F for $Q = 100{,}000$ Btu per second and is directly proportional to Q on the basis of the performance of the same type of heat exchanger in the turbojet cycle of reference 4. The 50° F is conservatvie inasmuch as it is based on total engine heat requirement rather than just on the basic-engine heat requirement, which is only a part of the total heat requirement. This assumption then gives the following relation for ΔT_z:

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$$\Delta T_z = \frac{50}{100{,}000} Q = 0.00050\ Q \tag{21}$$

The following is the relation used to compute ΔT_y:

$$\Delta T_y = \frac{Q}{4\ h_l \frac{l}{d} f\ A_{f,r}} \tag{22}$$

where from reference 10

$$h_l = \frac{k_l}{d_r}\left[7 + 0.025\left(\frac{\rho_l\ V_l\ d_r\ c_{p,l}}{k_l}\right)^{0.8}\right]$$

For lithium, ΔT_y is given by the following equation (using equation (22) and data from reference 11):

$$\Delta T_y = 0.000035\ Q \tag{23}$$

Then referring to equations (20), (21), and (23)

$$T_m = T_w + 0.000535\ Q$$

RESULTS AND DISCUSSION

Engine Performance

Two cases of ducted-fan operation are considered in the present report. The first case considered assumes that T_w and T_4 are fixed at 2270° and 2000° R, respectively. A value of 2000° R for T_4 is current operating practice and can be attained easily with T_w of 2270° R. These temperatures lead to T_m corresponding to the best which can be expected with metallic materials. The T_w', T_3', M_2' were varied together with P_3/P_2 and P_2/P_1 to determine the conditions for best F_n/W_T. The results of this case are presented in detail.

In order to determine engine performance at reduced T_w, the second case is considered where $T_w = T_w'$. The values of T_3', M_2', P_3/P_2, and P_2/P_1 which give maximum F_n/W_T are then determined. The results of these calculations are compared with the first set. 2577

Optimum duct heat-exchanger inlet Mach number M_2'. - In figure 3, F_n/W_T is plotted as a function of M_2'; T_3' is held at 1100° R for both parts of this figure. Figures 3(a) and 3(b) are for a flight altitude of 50,000 feet and M_0 of 0.9 and 1.5, respectively. The basic engine is operating with $T_w = 2270°$ R, $T_4 = 2000°$ R, and $M_3 = 0.15$.

Several combinations of P_2/P_1, P_3/P_2, and T_w' are illustrated. For $M_0 = 0.9$ (fig. 3(a)), the optimum M_2' is about 0.24 or slightly under, while for a flight Mach number of 1.5 (fig. 3(b)), the optimum occurs around 0.24 or slightly higher. The curves indicate that thrust per engine-plus-heat-exchanger weight is not very sensitive to duct-inlet Mach number.

Optimum fan pressure ratio P_2/P_1. - In figures 4 to 11, F_n/W_T and F_n/w_a are plotted as functions of P_2/P_1 for various values of T_3', P_3/P_2 of 1, 5, and 10, and T_w' of 1600°, 1800°, 2000°, and 2200° R. The basic engine is operating with T_w of 2270° R, T_4 of 2000° R, and M_3 of 0.15. These figures show all the engine performance optimized for M_2'.

In general, increasing the P_3/P_2 decreases the optimum P_2/P_1 for a given value of T_w' and T_3'. In addition, it can be seen that there is an optimum P_3/P_2 for a given value of T_w' and T_3'. Furthermore, there is an optimum T_3' for each T_w'. The optimum P_2/P_1, P_3/P_2, and T_3' obtained from these figures are presented later in the report.

Reactor heat release per pound of total air flow Q/w_a and ratio of basic-engine air flow to total air flow w_e/w_a. - Values of Q/w_a are shown as a function of P_2/P_1 and T_3' in figures 12 and 13 for M_0 of 0.9 and 1.5, respectively, and altitude of 50,000 feet. These values correspond to the engine conditions in figures 4 to 11. Values of w_e/w_a are shown in figures 14 and 15 for the same flight and engine conditions as the previous figures.

Optimum engine performance. - The optimum engine performance obtained from figures 4 to 15 is presented in figures 16 and 17 for M_0 of 0.9 and 1.5, respectively. The maximum F_n/W_T is plotted as a function of T_w' in parts (a) of figures 16 and 17. The corresponding values of F_n/w_a and Q/w_a are also shown in parts (a). Parts (b) of figures 16 and 17 show the values of T_3', w_e/w_a, P_3/P_2, and P_2/P_1 which give the maximum F_n/W_T indicated in parts (a).

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At $M_0 = 0.9$, the F_n/W_T varies from about 0.52 to 0.62 as T_w' varies from 1600° to 2200° R. The corresponding values of F_n/w_a are about 28 and 36, and of Q/w_a, 162 and 237, respectively. The optimum P_3/P_2 varies from about 6.7 to 6.6 and optimum P_2/P_1 varies from about 2.4 to 2.6. The optimum T_3' varies from about 1150 to 1600° R as T_w' varies from 1600 to 2200° R.

At $M_0 = 1.5$, the optimum F_n/W_T varies from 0.82 to 1.02 as T_w' varies from 1600 to 2200° R. The corresponding values of F_n/w_a are 23.4 and 26.3, and of Q/w_a, 153 and 203, respectively. The optimum P_3/P_2 varies from about 5.9 to 6.9 and the optimum P_2/P_1 varies from 1.8 to 1.3. The optimum T_3' varies from 1200 to 1400° R as T_w' varies from 1600° to 2200° R.

Effect of varying basic-engine heat-exchanger effective wall temperature T_w. - Up to this point, T_w has been fixed at 2270° R. In order to determine the effect of lower T_w on engine performance, T_w was assumed to be equal to T_w', which is varied from 1400 to 2200° R. Figure 18 shows the results of these calculations compared with the case where T_w is 2270° R. The maximum F_n/W_T is plotted as a function of T_w' for the two cases. The corresponding values of F_n/w_a are also shown. As expected at a T_w' of 2270° R, the dashed curve which represents engine operation with $T_w = 2270°$ R crosses the solid curve which represents operation with $T_w = T_w'$.

At M_0 of 0.9 for a T_w' of 1600° R, the F_n/W_T for the case of $T_w = T_w'$ is 35 percent less than where $T_w = 2270°$ R. At M_0 of 1.5, the F_n/W_T is similarly 33 percent less.

Airplane Performance

Airplane performance is presented in terms of W_g, Q, and T_m for maximum F_n/W_T (minimum W_g) for M_0 of 0.9 and 1.5 and for an altitude of 50,000 feet. Both cases of engine operation ($T_w = 2270°$ R and $T_w = T_w'$)

are considered. In the case of M_0 of 1.5, two values of L/D (6 and 9) are shown.

Gross weight W_g, reactor heat release Q, and reactor maximum wall temperature T_m. - Figures 19 to 22 show W_g in pounds, as a function of Q in Btu per second for W_s/W_g of 0.25 and 0.35, for values of W_K of 100,000 to 200,000 pounds, for T_w' of 1600°, 1800°, 2000°, and 2200° R, and for M_0 of 0.9 and 1.5. Figure 23 shows T_m as a function of Q for a range of T_w from 1400° to 2270° R.

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In the case where T_w = 2270° R (figs. 19 and 20), the gross weight increases as T_w' is reduced, for a given value of W_K, but Q decreases. The following table lists typical values of W_g, Q, and T_m found from figures 19, 20, and 23 for a value of W_K equal to 150,000 pounds.

M_0	L/D	T_w (°R)	T_w' (°R)	W_s/W_g	W_g (lb)	Q (Btu/sec)	T_m
0.9	18	2270	1800	0.35	273,000	91,000	2320
		2270	1800	.25	231,000	77,100	2310
1.5	6	2270	1800	.35	325,000	383,000	2470
		2270	1800	.25	267,000	308,000	2435

For convenience, table I lists all of the optimum engine conditions and the factors necessary to calculate W_g, w_a, and Q for any desired value of W_K for T_w of 2270° R, for W_s/W_g of 0.35 and 0.25, and for several values of T_w'. Also shown is the fan frontal area per pound of total air flow and the shell frontal area per pound of total air flow. The shell frontal area is the sum of the basic-engine and duct heat-exchanger frontal areas. The corresponding T_m can be found by use of figure 23.

Figures 21 and 22 present the second case where $T_w = T_w'$ for M_0 of 0.9 and 1.5 and an altitude of 50,000 feet. The following table lists typical values of W_g, Q, and T_m found from figures 21 to 23 for W_K equal to 150,000 pounds:

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M_0	L/D	T_w (^{o}R)	T_w' (^{o}R)	W_s/W_g	W_g (lb)	Q (Btu/sec)	T_m (^{o}R)
0.9	18	1800	1800	0.35	288,000	106,000	1858
		1800	1800	.25	241,000	89,600	1850
1.5	6	1800	1800	.35	367,000	517,000	2080
		1800	1800	.25	292,000	413,000	2020

For convenience, table II lists all of the optimum engine conditions and the factors necessary to calculate W_g and Q for any desired value of W_K for the case of $T_w = T_w'$ and $W_s/W_g = 0.35$ and 0.25. As in table I, the fan and shell frontal areas per pound of total air flow are also shown. The corresponding T_m can be found by use of figure 23.

Effect of altitude. - The effect of altitude on W_g/W_K and Q/W_K for W_s/W_g of 0.35, T_w' of 1800° R, and T_w of 2270° R is shown in figure 24 for flight Mach numbers of 0.9 and 1.5, respectively. The optimum values of P_2/P_1, P_3/P_2, and T_3' found for an altitude of 50,000 feet are used for the range of altitudes shown. For M_0 of 0.9, W_g/W_K and Q/W_K are relatively constant from sea level to about 50,000 feet, above which they begin to increase rapidly. For a M_0 of 1.5, the same is true up to altitudes of 40,000 feet, above which W_g/W_K and Q/W_K begin to increase rapidly.

Comparison of turbojet cycle with ducted-fan cycle. - The liquid-metal ducted-fan cycle is compared with the liquid-metal turbojet cycle from reference 4 on the basis of minimum W_g and corresponding Q in figure 25. For both cycles and for M_0 of 0.9 and 1.5, W_s/W_g is assumed to be 0.35 and W_K is assumed to be 150,000 pounds. The airplane L/D for the M_0 of 1.5 is assumed to be 6. In both cases, W_g and Q are plotted as a function of T_w. The W_g of the ducted-fan installation appears to be about equal to that of the turbojet installation; however, Q is about 10 percent higher than for the turbojet at M_0 of 0.9 and about 20 percent higher at M_0 of 1.5. The scope of this present report does not include off-design performance and so this possible advantage of the ducted fan is not indicated by the design-point comparison made in figure 25.

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SUMMARY OF RESULTS

1. The following table lists the optimum engine conditions for the liquid-metal ducted-fan cycle in the case where the basic-engine heat-exchanger effective wall temperature is 2270° R and for two duct heat-exchanger effective wall temperatures.

Flight Mach number M_0	Lift drag ratio L/D	Duct heat-exchanger effective wall temperature T_w' (°R)	Compressor pressure ratio P_3/P_2	Fan pressure ratio P_2/P_1	Duct-outlet air temperature T_3' (°R)	Net thrust per engine-plus-heat-exchanger weight F_n/W_T	Net thrust per pound of total air flow F_n/w_a	Reactor heat release per pound of total air flow Q/w_a
0.9	18	1600	6.75	2.35	1150	0.524	28.0	162
		2200	6.60	2.57	1590	.618	35.7	237
1.5	6	1600	5.93	1.80	1195	.813	23.4	153
		2200	6.85	1.29	1410	1.018	26.3	203

2. The following table lists the optimum engine conditions for the liquid-metal ducted-fan cycle in the case where the basic-engine heat-exchanger effective wall temperature is equal to the duct heat-exchanger effective wall temperature.

Flight Mach number M_0	Lift-drag ratio L/D	Basic engine heat-exchanger effective wall temperature T_w (°R)	Duct heat-exchanger effective wall temperature T_w' (°R)	Compressor pressure ratio P_3/P_2	Fan pressure ratio P_2/P_1	Duct-outlet air temperature T_3' (°R)	Net thrust per engine-plus-heat-exchanger F_n/W_T	Net thrust per pound of total air flow F_n/w_a	Reactor heat release per pound of total air flow Q/w_a
0.9	18	1800	1800	4.6	2.0	1260	0.4332	27.0	181
1.5	6	1800	1800	5.0	1.2	1260	.6942	19.7	166

3. The required gross weight, reactor heat release, and maximum reactor wall temperature for flight Mach numbers of 0.9 and 1.5, an altitude of 50,000 feet, the sum of the reactor shield, payload, and auxiliary weight of 150,000 pounds, and a basic-engine and duct heat-exchanger effective wall temperature of 1800° R are as follows:

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Flight Mach number M_0	Lift-drag ratio L/D	Structure-to-gross-weight ratio W_s/W_g	Gross weight W_g (lb)	Reactor heat release Q (Btu/sec)	Reactor maximum wall temperature T_m ($^{\circ}R$)
0.9	18	0.35	288,000	106,600	1858
		.25	241,000	89,600	1850
1.5	6	.35	367,000	517,000	2080
		.25	292,000	413,000	2020

4. The effect of changing altitude on airplane gross weight and reactor heat release is small from sea level to 50,000 feet and from sea level to 40,000 feet for flight Mach numbers of 0.9 and 1.5, respectively. Above these altitudes, both the gross weight and reactor heat release increase rapidly.

5. The required design-point gross weight of the ducted-fan cycle operating at 50,000 feet and flight Mach numbers of 0.9 and 1.5 is about the same as the required gross weight of the turbojet cycle for the same heat-exchanger effective wall temperature. The reactor heat release of the ducted-fan cycle, however, is about 10 to 20 percent higher than for the turbojet.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 12, 1952

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TABLE I - OPTIMUM ENGINE CONDITIONS FOR BASIC-ENGINE HEAT-EXCHANGER EFFECTIVE WALL TEMPERATURE OF 2270° R

Flight Mach number M_0	Airplane lift-drag ratio L/D	Structure to-gross-weight ratio W_s/W_g	Basic-engine heat-exchanger effective wall temperature (°R) T_w	Duct heat-exchanger effective wall temperature (°R) T_w'	Compressor pressure ratio P_3/P_2	Fan pressure ratio P_2/P_1	Duct-outlet air temperature (°R) T_3'	Net thrust per engine-plus-heat-exchanger weight F_n/W_T	Net thrust per pound of total air flow F_n/w_a	Reactor heat release per pound of total air flow Q/w_a	Gross weight per reactor-plus-payload-plus-auxiliary weight W_g/W_K	Total air flow per reactor-plus-shield-plus-payload-plus-auxiliary weight w_a/W_K	Reactor heat release per reactor-plus-shield-plus-payload-plus-auxiliary weight Q/W_K	Fan frontal area per pound of total air flow A_f/w_a	Shell frontal area per pound of total air flow A_d/w_a
0.9	18	0.35	2270	1600	6.75	2.35	1150	0.524	28.0	162	1.838	0.003647	0.5908	0.201	0.153
				1800	6.70	2.48	1290	.555	30.6	184	1.819	.003302	.6076		.144
				2000	6.65	2.54	1440	.586	33.1	209	1.801	.003023	.6318		.140
				2200	6.60	2.57	1590	.618	35.7	237	1.785	.002778	.6584		.138
0.9	18	0.25	2270	1600	6.75	2.35	1150	0.524	28.0	162	1.553	0.003081	0.4991	0.201	0.153
				1800	6.70	2.48	1290	.555	30.6	184	1.539	.002794	.5141		.144
				2000	6.65	2.54	1440	.586	33.1	209	1.526	.002561	.5352		.140
				2200	6.60	2.57	1590	.618	35.7	237	1.515	.002358	.5588		.138
1.5	6	0.35	2270	1400	5.55	2.03	1100	0.745	22.0	138	2.346	0.01777	2.443	0.105	0.085
				1600	5.93	1.80	1195	.813	23.4	153	2.247	.01599	2.446		.098
				1800	6.30	1.60	1275	.880	24.5	169	2.171	.01476	2.494		.113
				2000	6.60	1.42	1345	.950	25.5	186	2.107	.01377	2.561		.130
				2200	6.85	1.29	1410	1.018	26.3	203	2.056	.01302	2.643		.147
1.5	6	0.25	2270	1400	5.55	2.03	1100	0.745	22.0	138	1.900	0.01439	1.986	0.105	0.085
				1600	5.93	1.80	1195	.813	23.4	153	1.835	.01307	2.000		.098
				1800	6.30	1.60	1275	.880	24.5	169	1.784	.01214	2.052		.113
				2000	6.60	1.42	1345	.950	25.5	186	1.740	.01137	2.115		.130
				2200	6.85	1.29	1410	1.018	26.3	203	1.706	.01081	2.194		.147
1.5	9	0.35	2270	1400	5.55	2.03	1100	0.745	22.0	138	1.997	0.01008	1.386	0.105	0.085
				1600	5.93	1.80	1195	.813	23.4	153	1.948	.00924	1.414		.098
				1800	6.30	1.60	1275	.880	24.5	169	1.909	.00865	1.462		.113
				2000	6.60	1.42	1345	.950	25.5	186	1.876	.00817	1.520		.130
				2200	6.85	1.29	1410	1.018	26.3	203	1.849	.00780	1.584		.147
1.5	9	0.25	2270	1400	5.55	2.03	1100	0.745	22.0	138	1.664	0.008404	1.160	0.105	0.085
				1600	5.93	1.80	1196	.814	23.4	153	1.631	.007745	1.185		.098
				1800	6.30	1.60	1275	.880	24.5	169	1.603	.007270	1.229		.113
				2000	6.60	1.42	1345	.950	25.5	186	1.580	.006885	1.281		.130
				2200	6.85	1.29	1410	1.018	26.3	203	1.560	.006591	1.338		.147

TABLE II - OPTIMUM ENGINE CONDITIONS FOR BASIC-ENGINE HEAT-EXCHANGER EFFECTIVE WALL TEMPERATURE

EQUAL TO DUCT HEAT-EXCHANGER EFFECTIVE WALL TEMPERATURE

Flight Mach number M_0	Airplane lift-drag ratio L/D	Structure to-gross-weight ratio W_s/W_g	Basic engine heat-exchanger effective wall temperature (°R) T_w	Duct heat-exchanger effective wall temperature (°R) T_w'	Compressor pressure ratio P_3/P_2	Fan pressure ratio P_2/P_1	Duct-outlet air temperature (°R) T_3'	Net thrust per engine-plus-heat-exchanger weight F_n/W_T	Net thrust per pound of total air flow F_n/w_a	Reactor heat release per pound of total air flow Q/w_a	Gross weight per reactor-plus-payload-plus-auxiliary weight W_g/W_K	Total air flow per reactor-plus-shield-plus-payload-plus-auxiliary weight w_a/W_K	Reactor heat release per reactor-plus-shield-plus-payload-plus-auxiliary weight Q/W_K	Fan frontal area per pound of total air flow A_f/w_a	Shell frontal area per pound of total air flow A_d/w_a
0.9	18	0.35	1400 1800 2270	1400 1800 2270	3.0 4.6 6.58	1.6 2.0 2.57	1000 1260 1630	0.2559 .4332 .629	17.53 27.00 36.6	125.7 180.5 246	2.310 1.916 1.781	0.007322 .003942 .002703	0.9200 .7116 .665	0.201	0.225 .179 .144
0.9	18	0.25	1400 1800 2270	1400 1800 2270	3.0 4.6 6.58	1.6 2.0 2.57	1000 1260 1630	0.2559 .4332 .629	17.53 27.00 36.6	125.7 180.5 246	1.877 1.608 1.511	0.005949 .003309 .002294	0.7478 .5973 .5643	0.201	0.225 .179 .144
1.5	6	0.35	1600 1800 2000	1600 1800 2000	4.0 5.0 4.0	1.2 1.2 1.4	1120 1260 1400	0.5459 .6942 .8334	16.52 19.73 25.76	132.1 166.0 212.3	2.901 2.440 2.222	0.02927 .02061 .01437	3.867 2.421 3.051	0.105	0.153 .157 .137
1.5	6	0.25	1600 1800 2000	1600 1800 2000	4.0 5.0 4.0	1.2 1.2 1.4	1120 1260 1400	0.5459 .6942 .8334	16.52 19.73 25.76	132.1 166.0 212.3	2.249 1.961 1.818	0.02269 .01656 .01178	2.997 2.749 2.497	0.105	0.153 .157 .137
1.5	9	0.35	1600 1800 2000	1600 1800 2000	4.0 5.0 4.0	1.2 1.2 1.4	1120 1260 1400	0.5459 .6942 .8334	16.52 19.73 25.76	132.1 166.0 212.3	2.240 2.041 1.935	0.01506 .01149 .00835	1.989 1.907 1.772	0.105	0.153 .157 .137
1.5	9	0.25	1600 1800 2000	1600 1800 2000	4.0 4.0 4.0	1.2 1.2 1.4	1120 1260 1400	0.5459 .6942 .8334	16.52 19.73 25.76	132.1 166.0 212.3	1.830 1.695 1.622	0.01231 .009544 .006997	1.626 1.584 1.485	0.105	0.153 .157 .137

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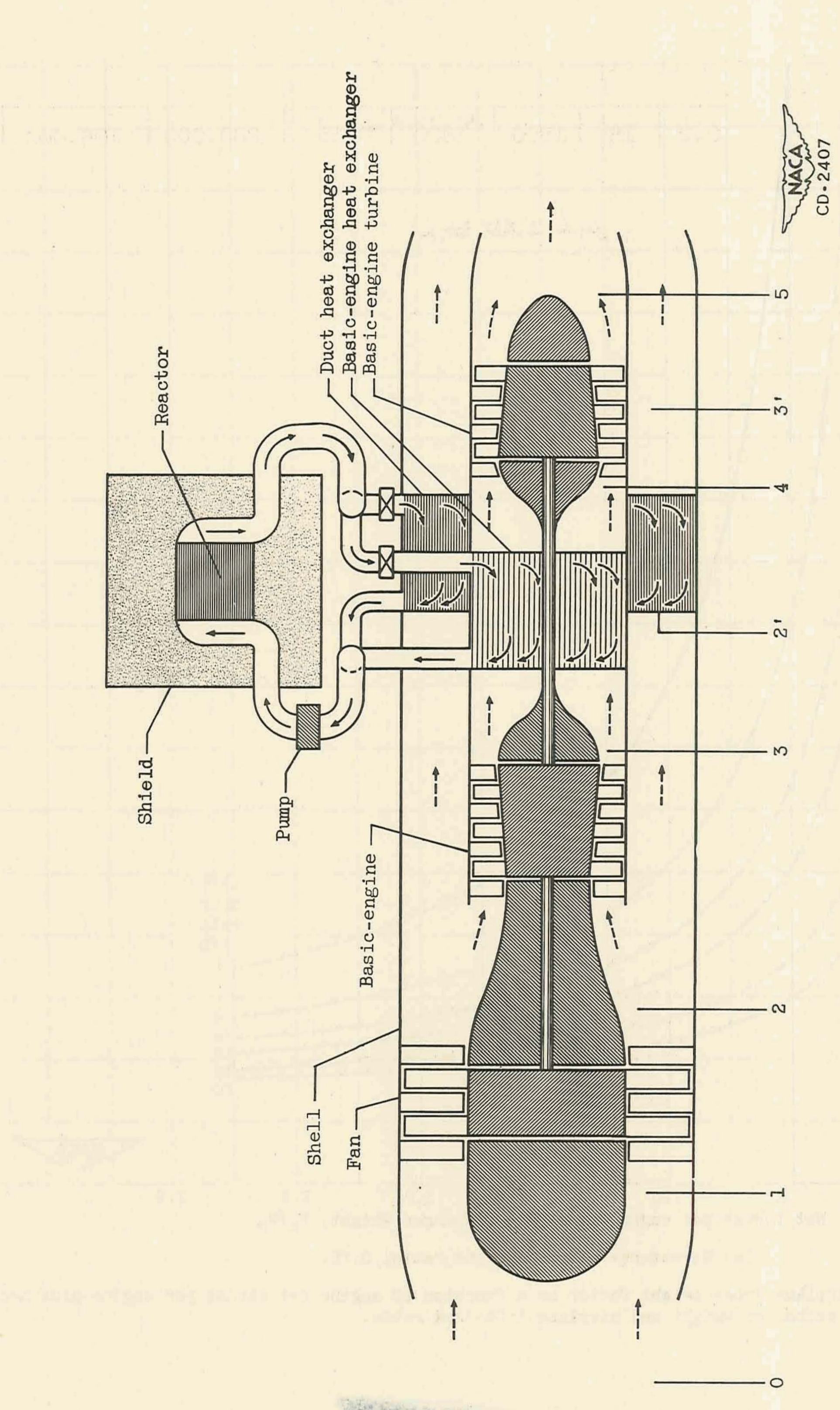

Figure 1. - Schematic diagram of the nuclear-powered liquid-metal ducted-fan cycle.

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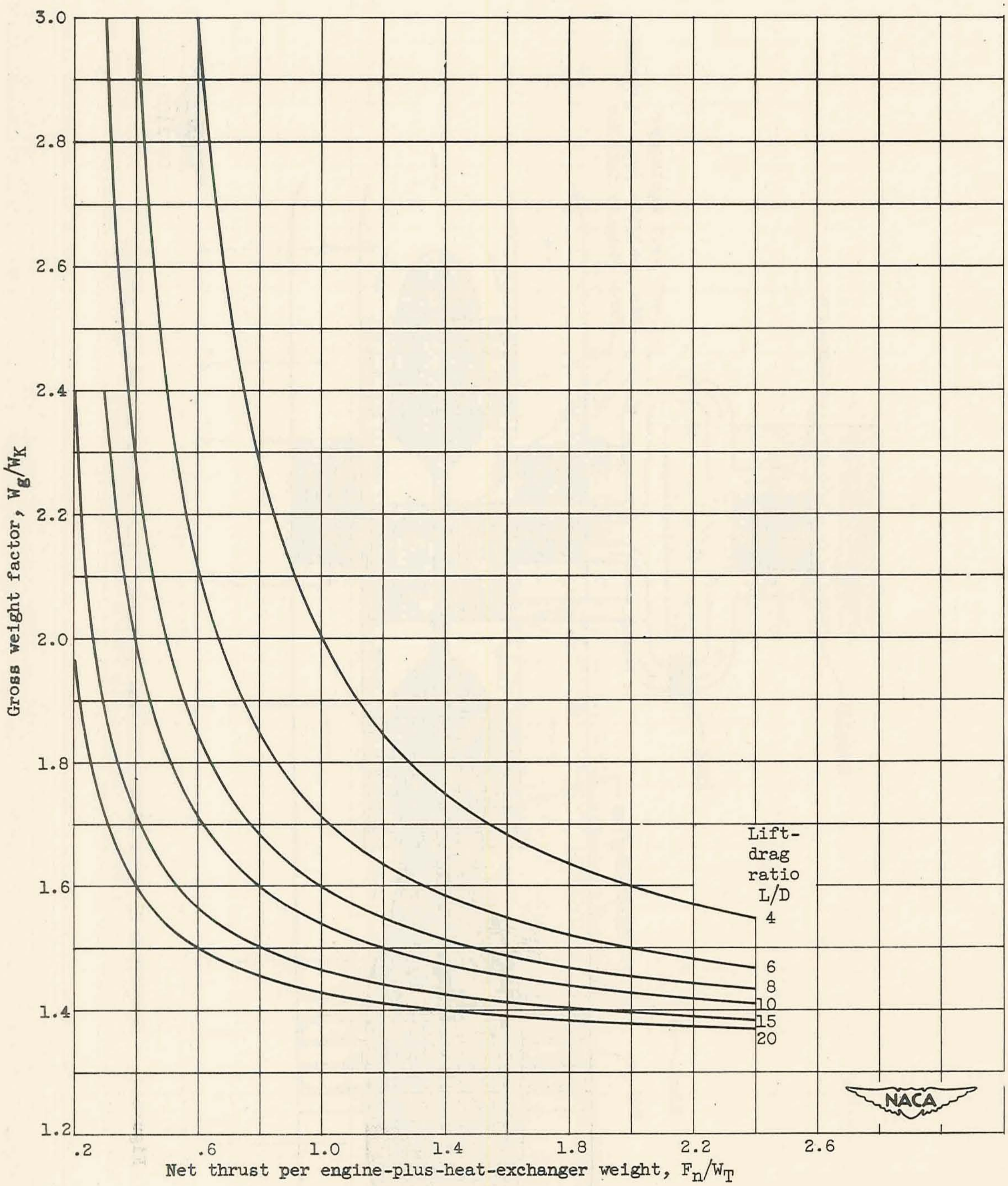

(a) Structure-to-gross-weight ratio, 0.25.

Figure 2. - Airplane gross weight factor as a function of engine net thrust per engine-plus-heat-exchanger weight and airplane lift-drag ratio.

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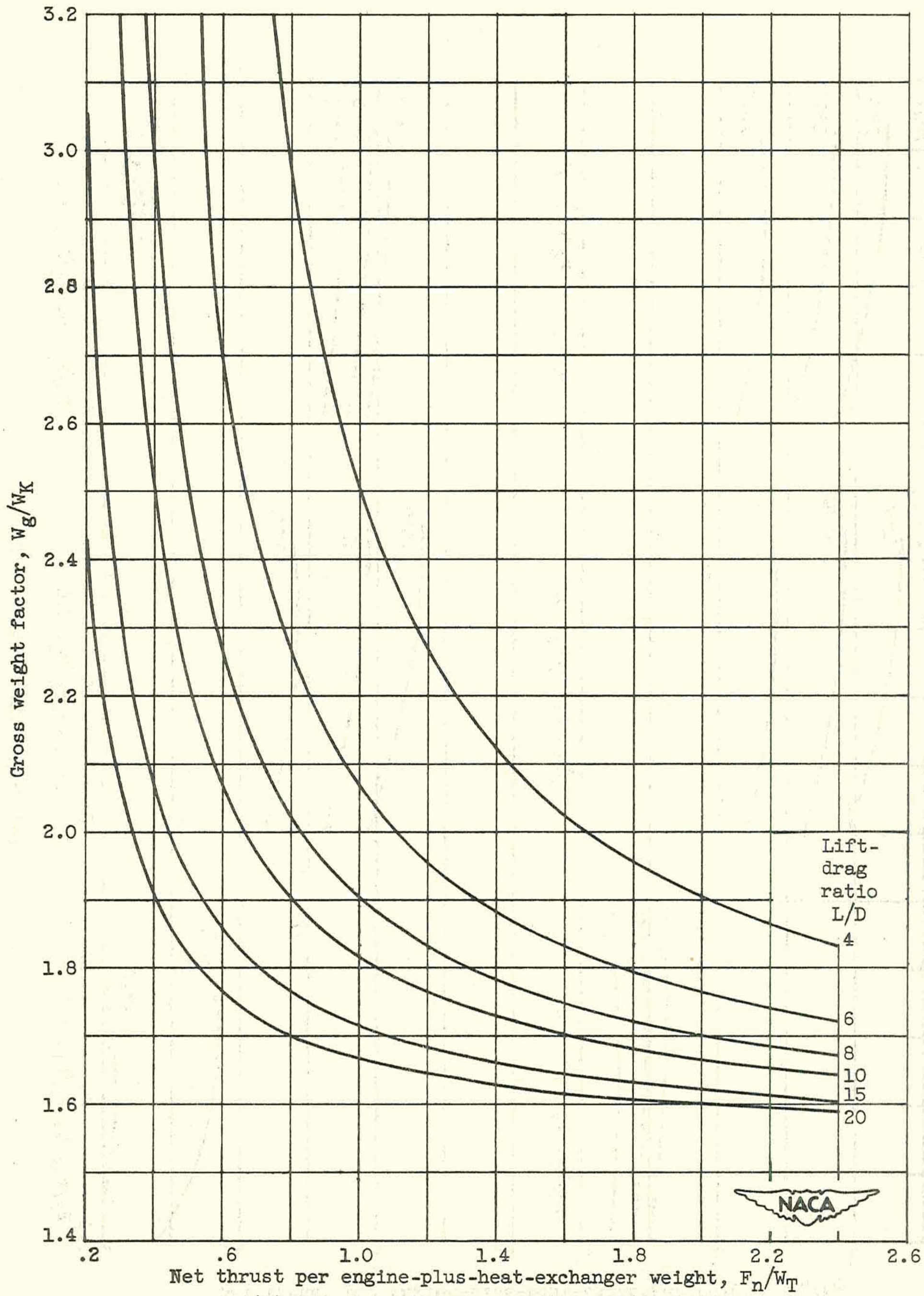
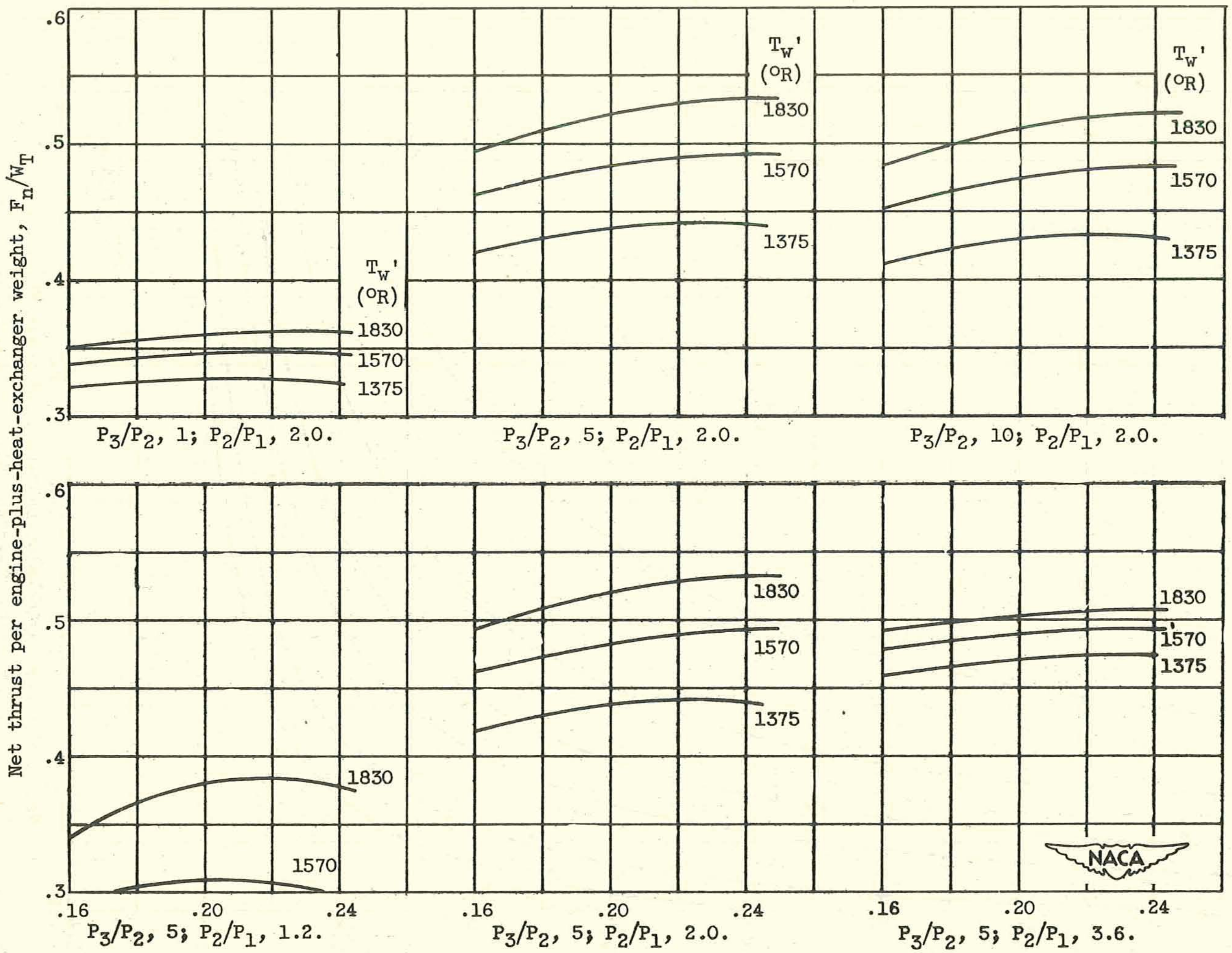


(b) Structure-to-gross-weight ratio, 0.35.

Figure 2. - Concluded. Airplane gross weight factor as a function of engine net thrust per engine-plus-heat-exchanger weight and airplane lift-drag ratio.



(a) Flight Mach number, 0.9.

Figure 3. - Effect of duct heat-exchanger inlet Mach number on net thrust per engine-plus-exchanger weight at several duct heat-exchanger effective wall temperatures T_W'. Altitude, 50,000 feet; basic-engine heat-exchanger wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct-outlet air temperature, 1100° R.

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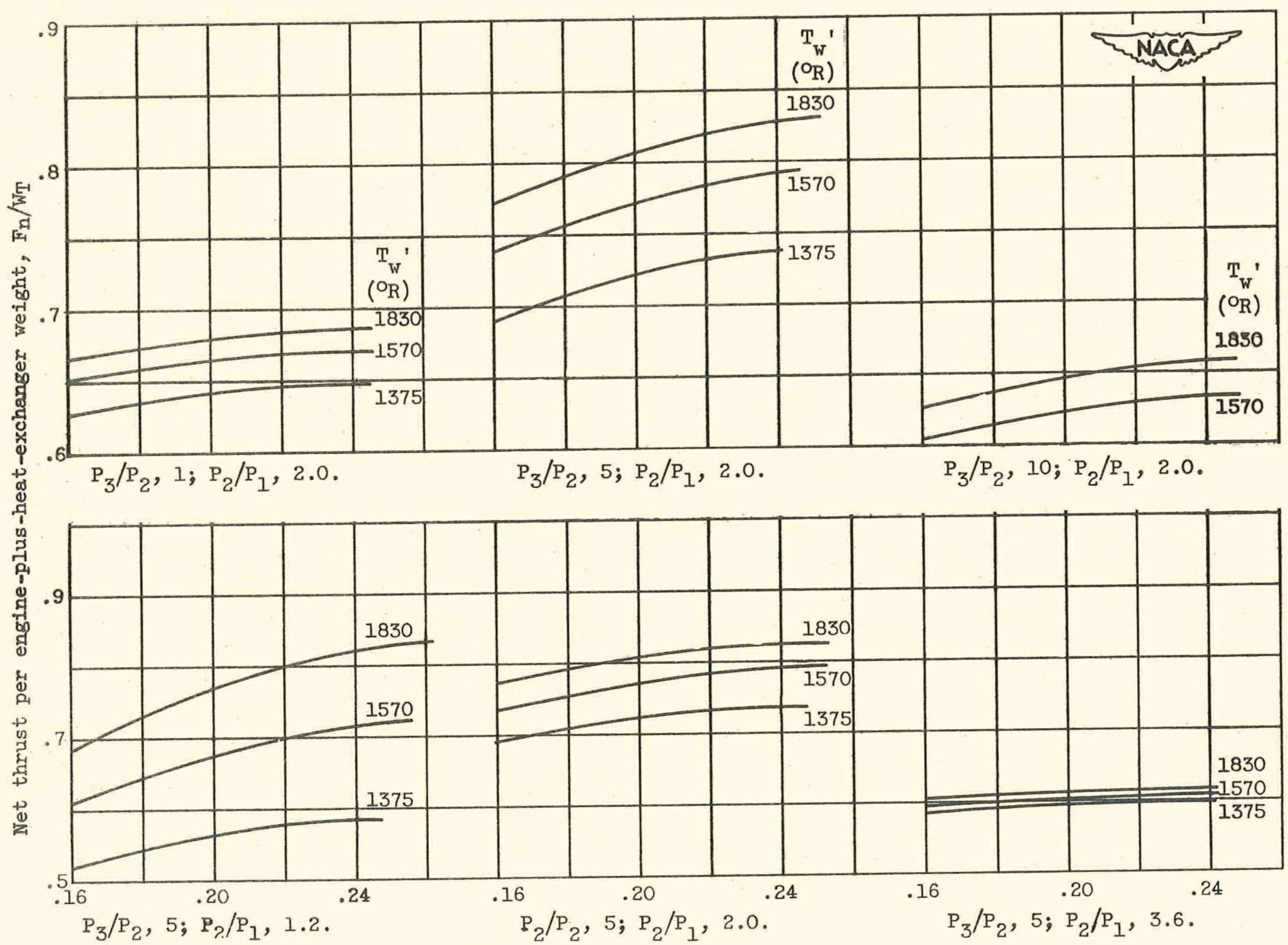
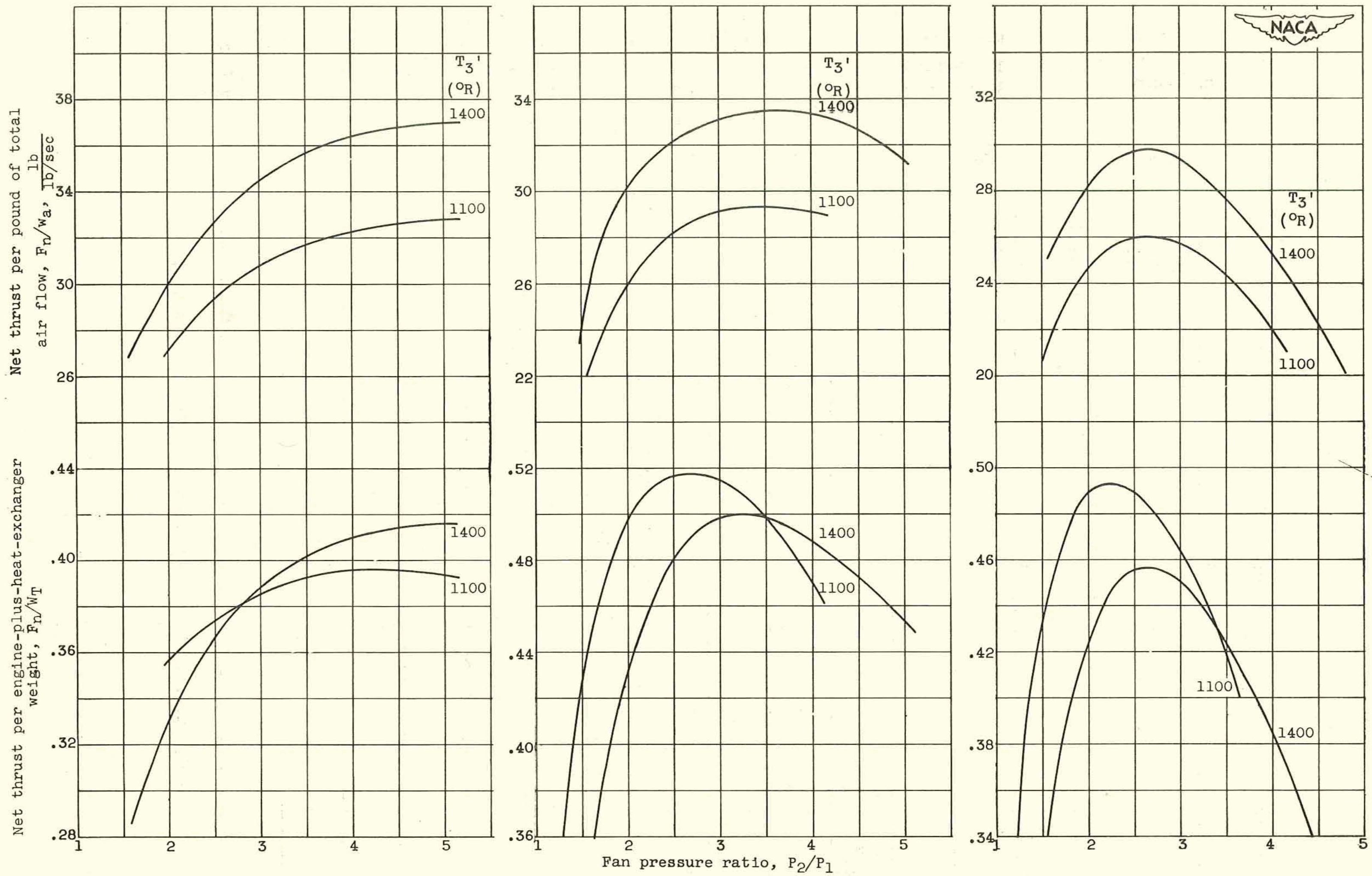


(b) Flight Mach number, 1.5.

Figure 3. - Concluded. Effect of duct heat-exchanger inlet Mach number on net thrust per engine-plus-exchanger weight at several duct heat-exchanger effective wall temperatures T_w'. Altitude, 50,000 feet; basic-engine heat-exchanger wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct-outlet air temperature, 1100° R.



(a) Compressor pressure ratio, 1.

(b) Compressor pressure ratio, 5.

(c) Compressor pressure ratio. 10.

Figure 4. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on net thrust per engine-plus-heat-exchanger weight and net thrust per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger effective wall temperature, 1600° R.

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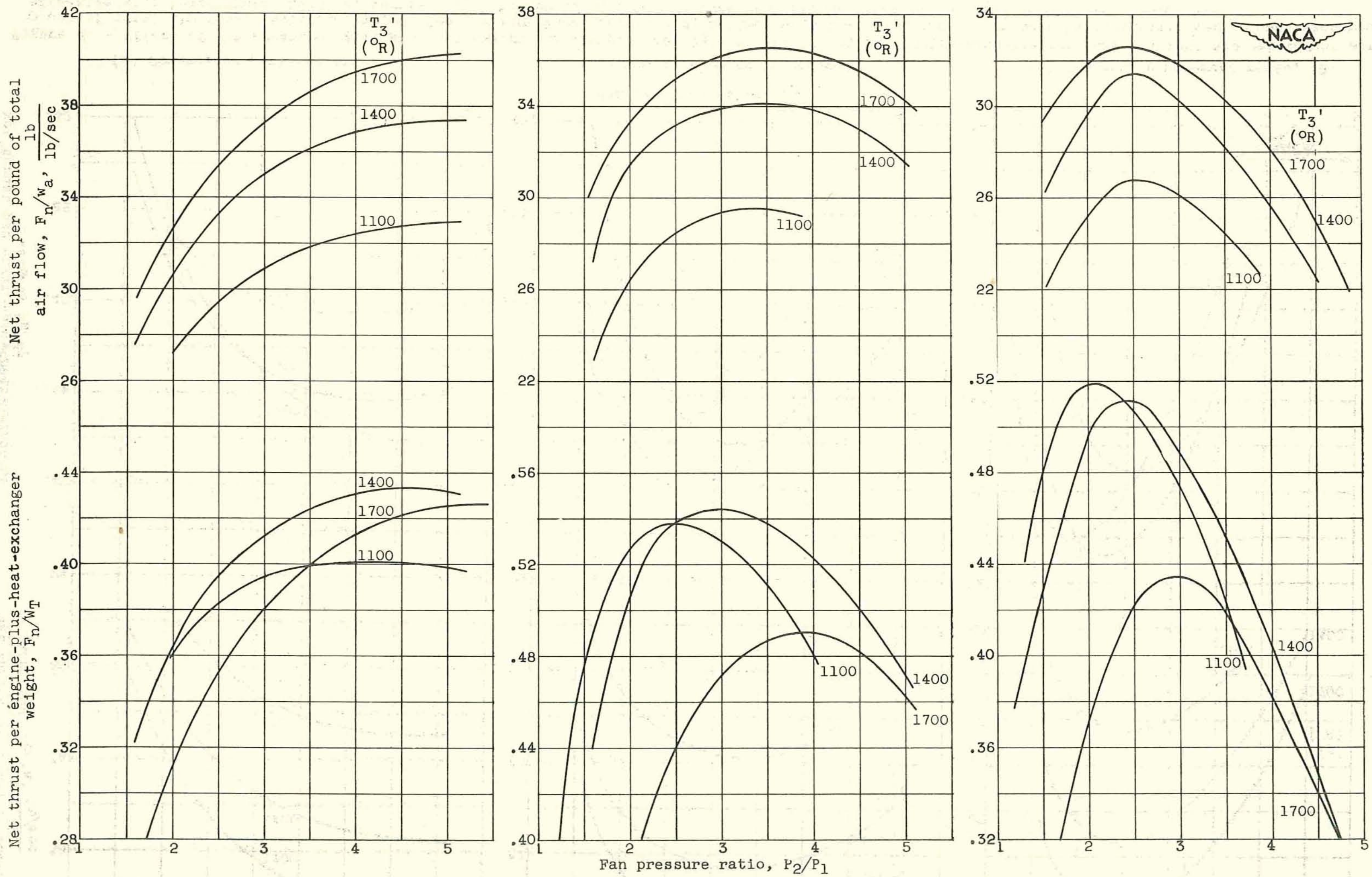
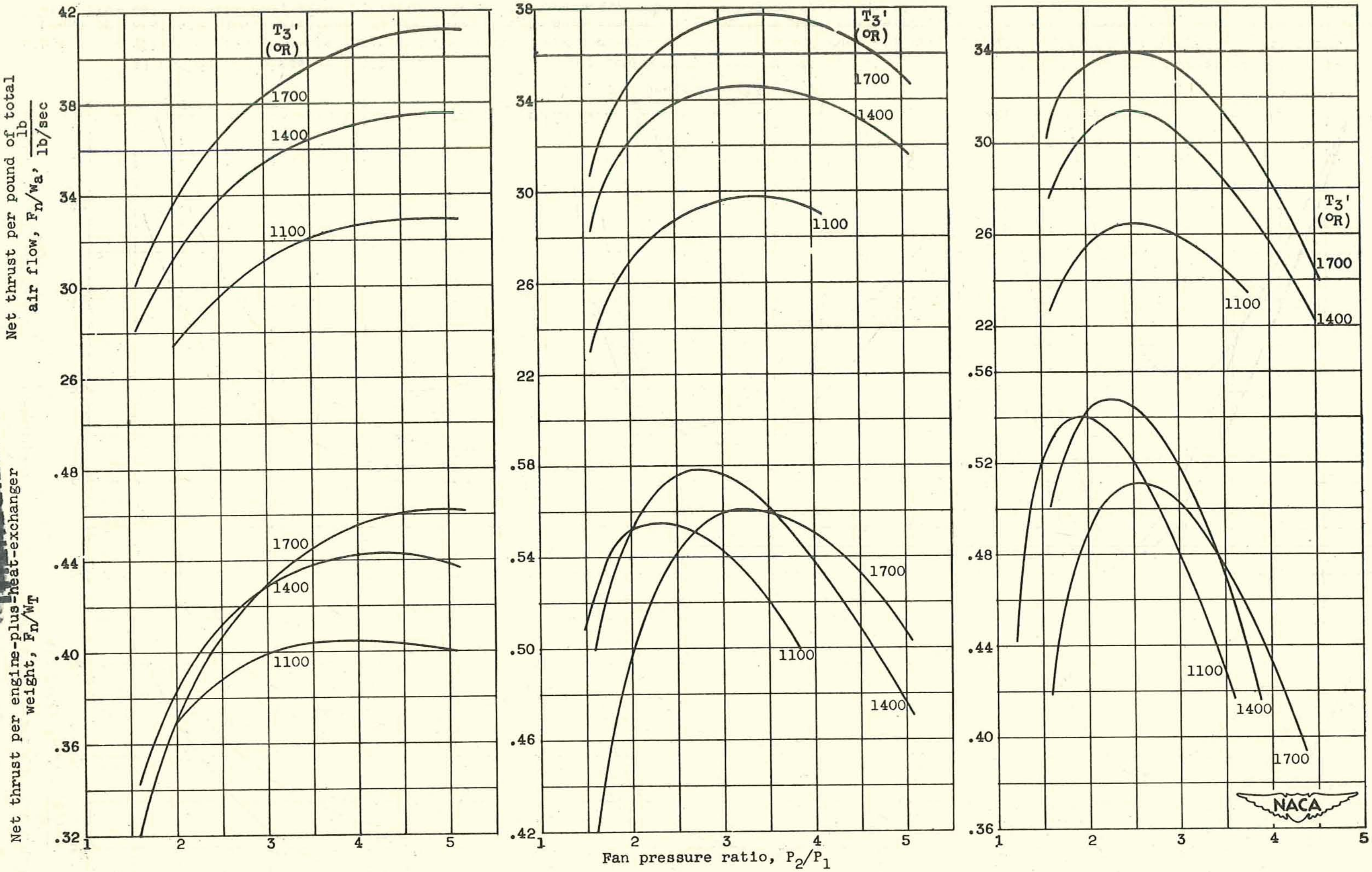


(a) Compressor pressure ratio, 1.

(b) Compressor pressure ratio, 5.

(c) Compressor pressure ratio, 10.

Figure 5. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on net thrust per engine-plus-heat-exchanger weight and net thrust per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; optimum duct heat exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger effective wall temperature, 1800° R.



(a) Compressor pressure ratio, 1.

(b) Compressor pressure ratio, 5.

(c) Compressor pressure ratio, 10.

Figure 6. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on net thrust per engine-plus-heat-exchanger weight and net thrust per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; optimum duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger effective wall temperature, 2000° R.

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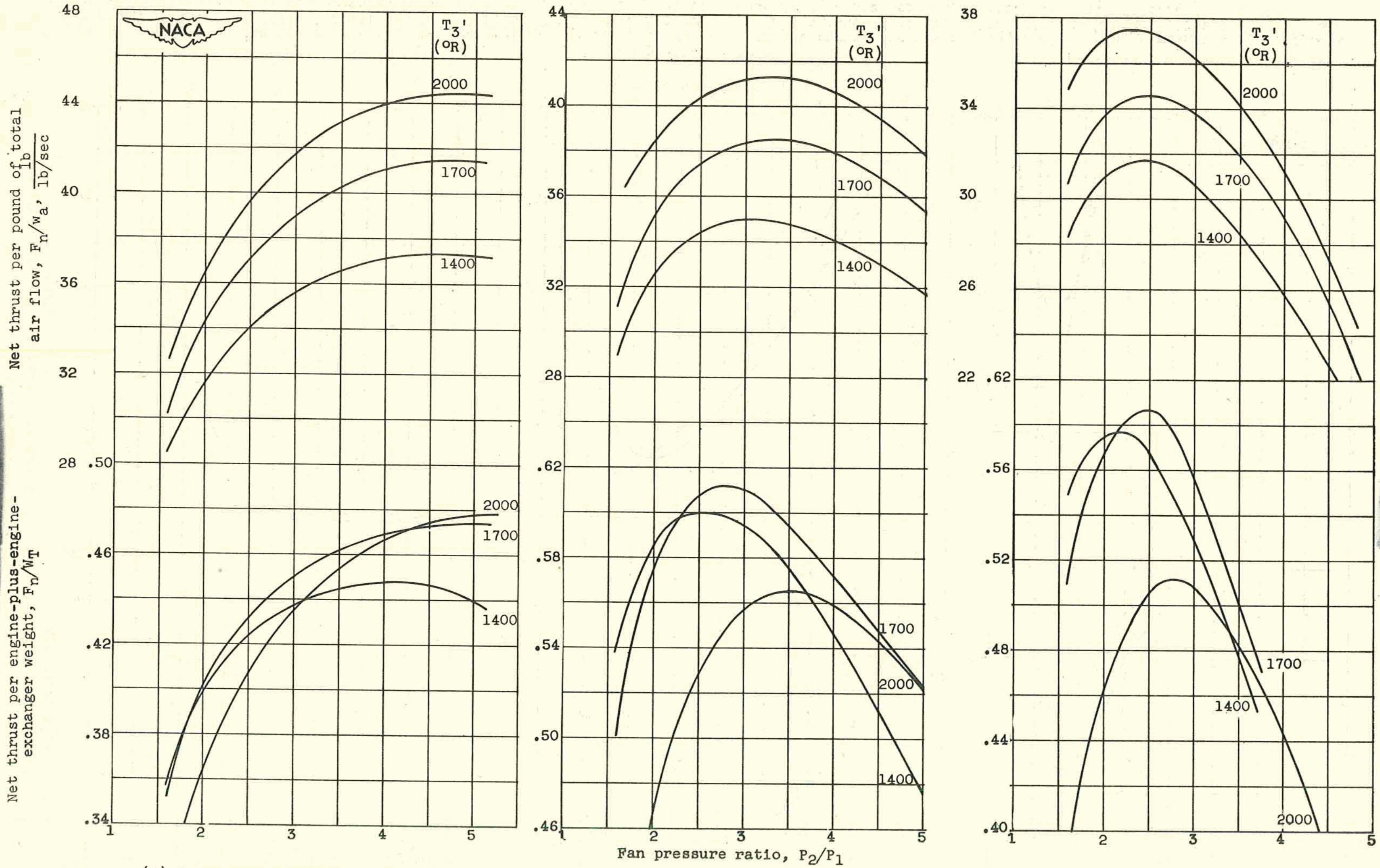

(a) Compressor pressure ratio, 1.

(b) Compressor pressure ratio, 5.

(c) Compressor pressure ratio, 10.

Figure 7. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on net thrust per engine-plus-heat-exchanger weight and net thrust per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; optimum duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger effective wall temperature, 2200° R.

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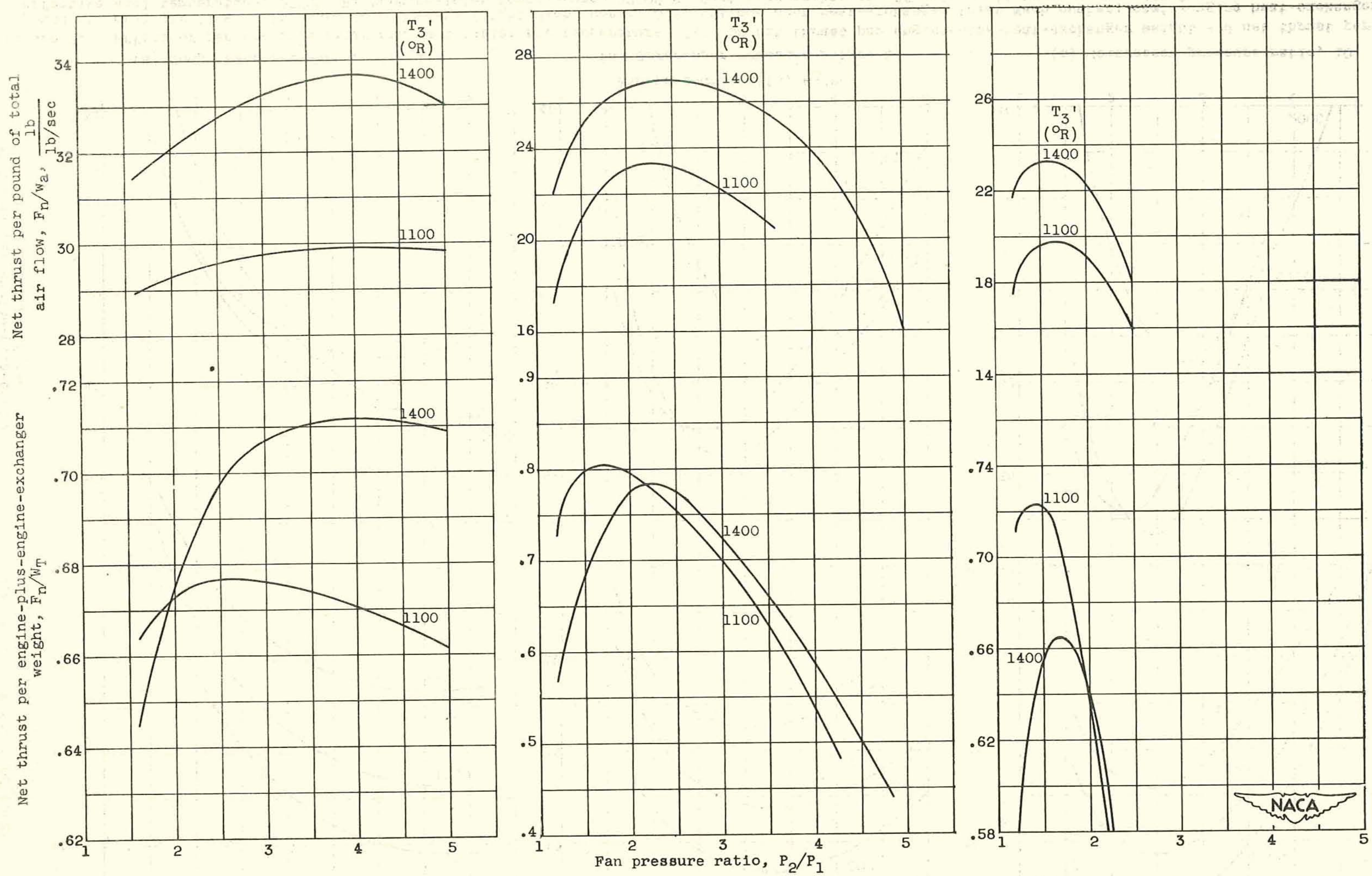

(a) Compressor pressure ratio, 1.

(b) Compressor pressure ratio, 5.

(c) Compressor pressure ratio, 10.

Figure 8. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on net thrust per engine-plus-heat-exchanger weight and net thrust per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; optimum duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger effective wall temperature, 1600° R.

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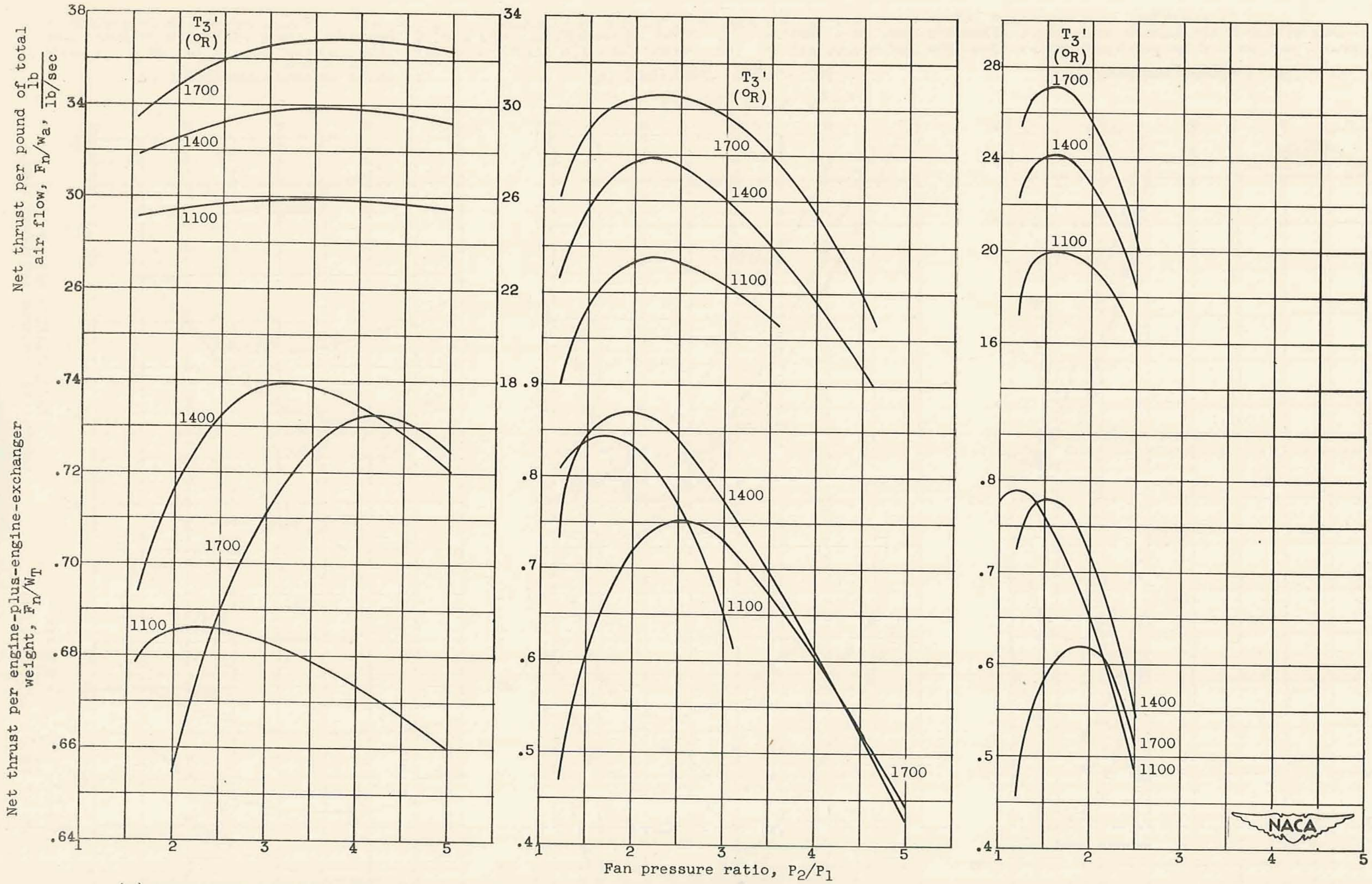

(a) Compressor pressure ratio, 1.

(b) Compressor pressure ratio, 5.

(c) Compressor pressure ratio, 10.

Figure 9. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on net thrust per engine-plus-heat-exchanger weight and net thrust per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; optimum duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger effective wall temperature, 1800° R.

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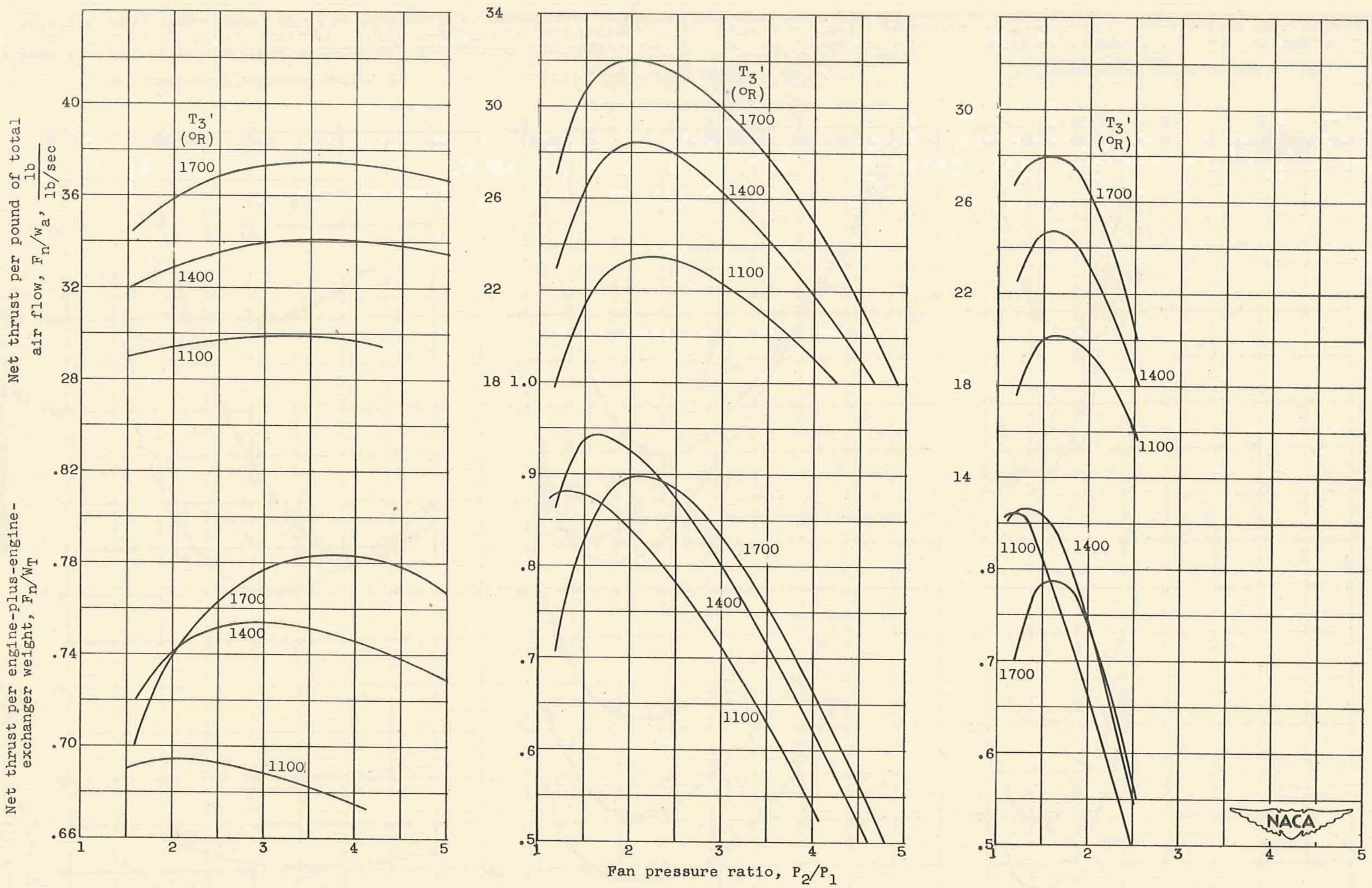

(a) Compressor pressure ratio, 1.

(b) Compressor pressure ratio, 5.

(c) Compressor pressure ratio, 10.

Figure 10. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on net thrust per engine-plus-heat-exchanger weight and net thrust per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; optimum duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger effective wall temperature, 2000° R.

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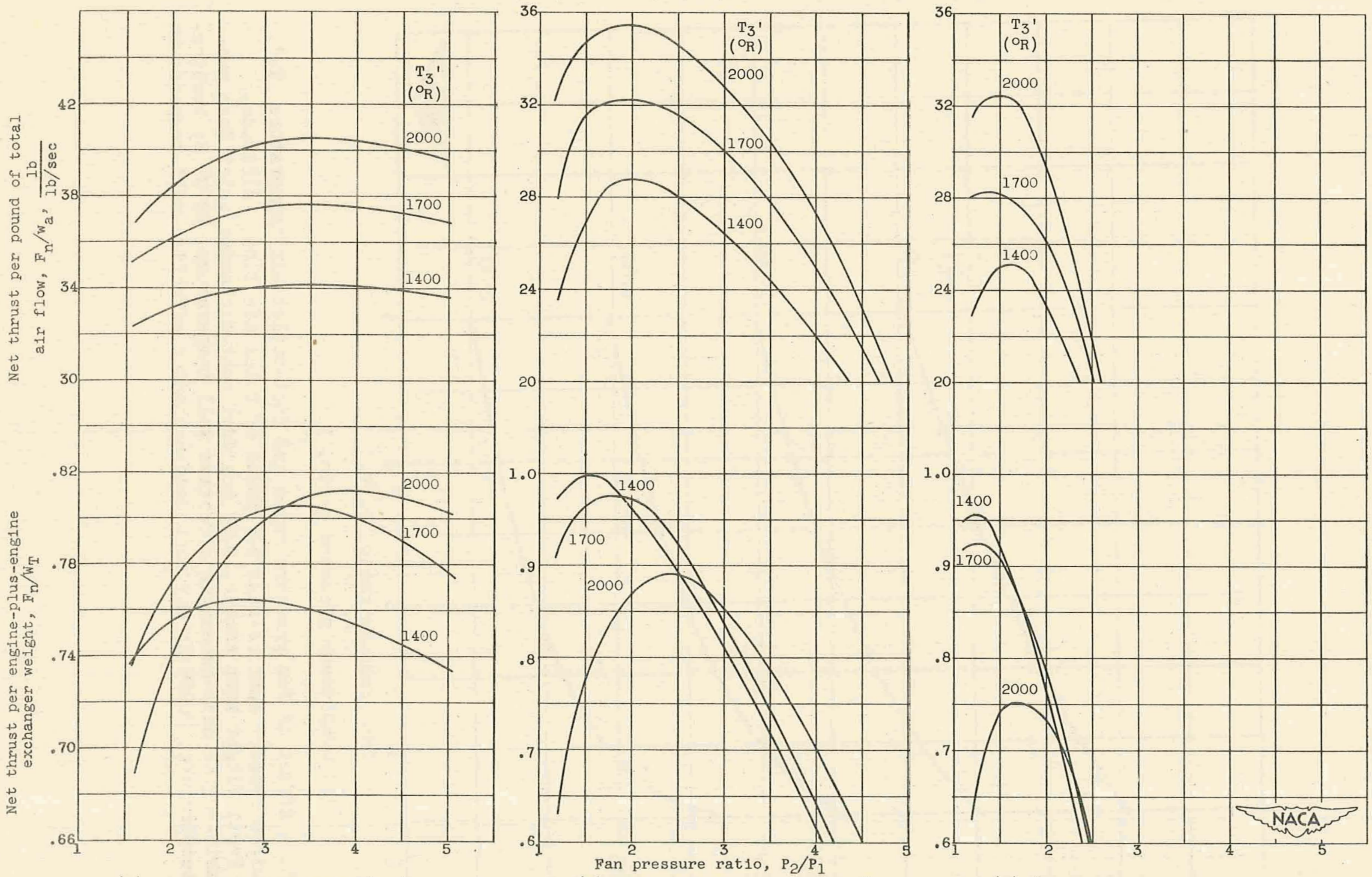

(a) Compressor pressure ratio, 1.

(b) Compressor pressure ratio, 5.

(c) Compressor pressure ratio, 10.

Figure 11. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on net thrust per engine-plus-heat-exchanger weight and net thrust per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; optimum duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger effective wall temperature, 2200° R.

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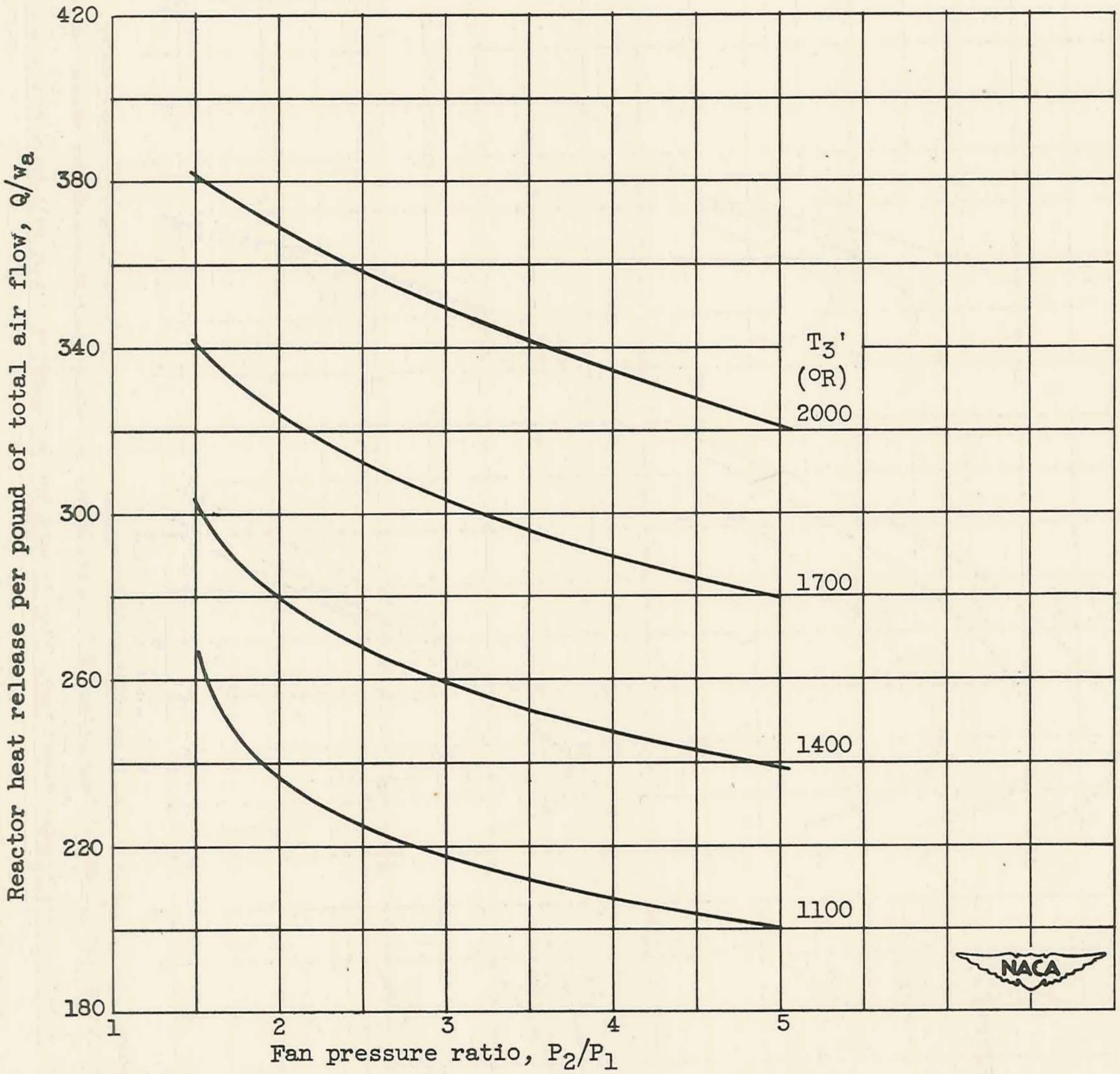
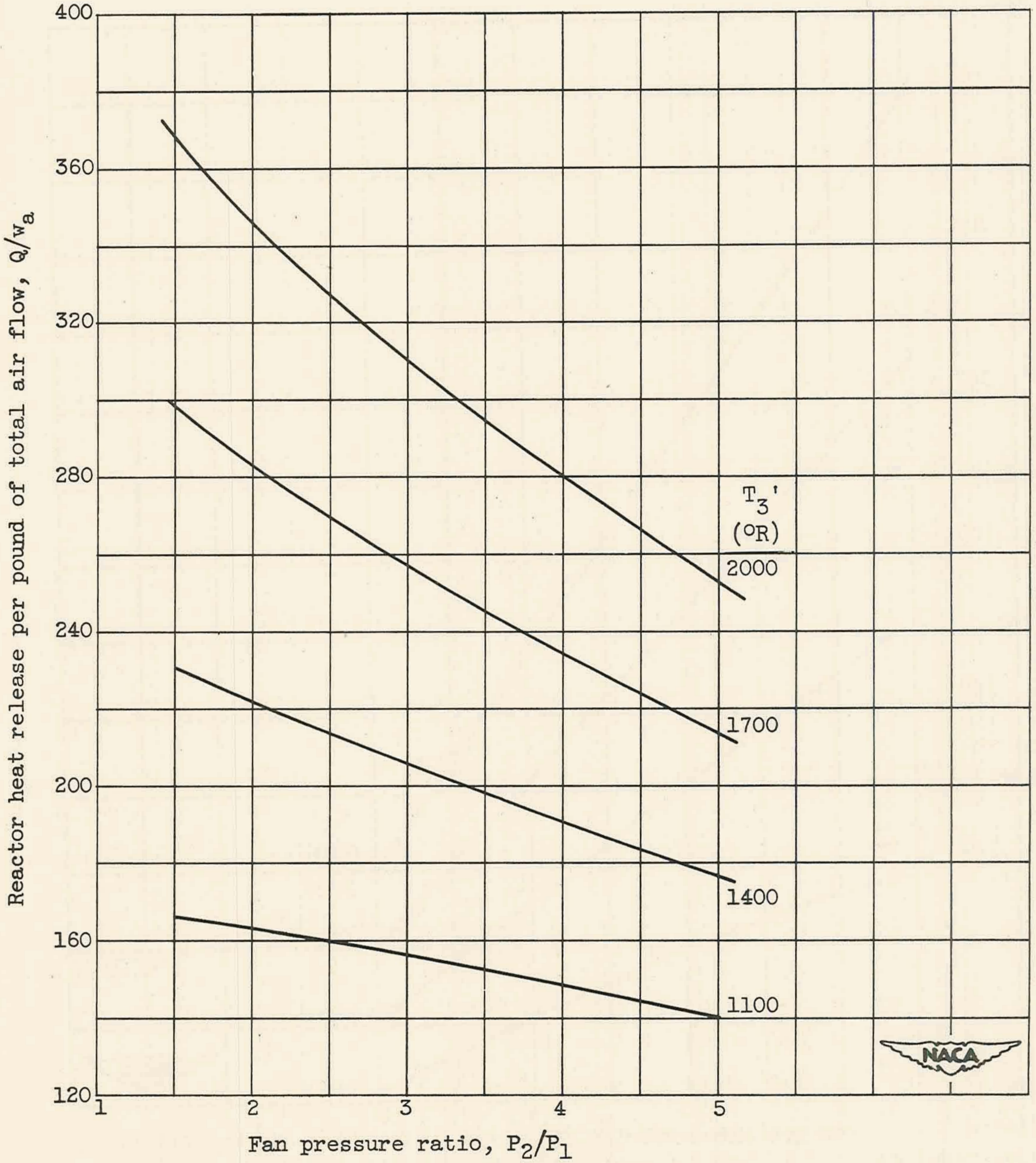


(a) Compressor pressure ratio, 1.

Figure 12. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on required reactor heat release per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; any duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.



(b) Compressor pressure ratio, 5.

Figure 12. - Continued. Effect of fan pressure ratio and duct-outlet air temperature T_3' on required reactor heat release per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; any duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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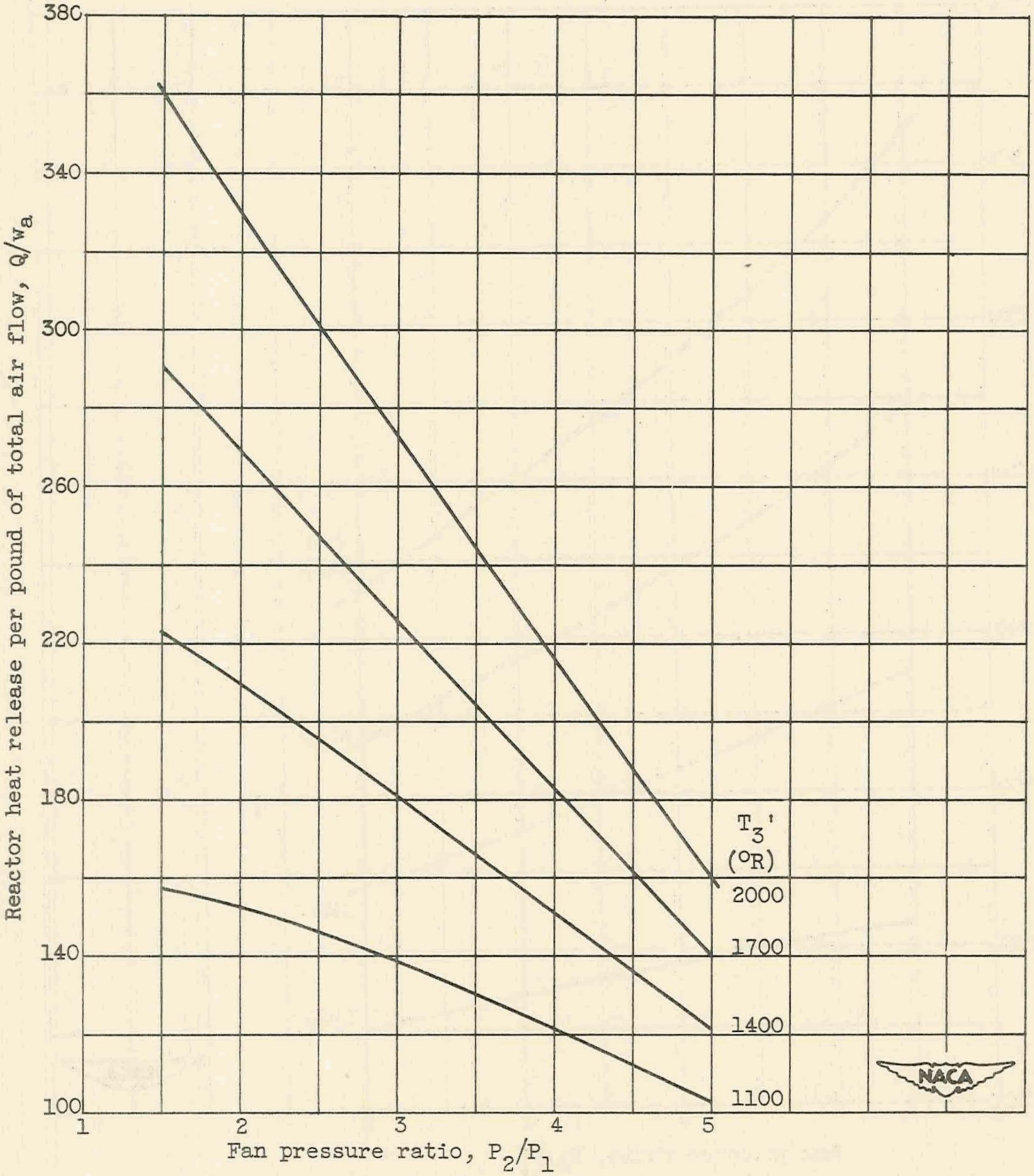

(c) Compressor pressure ratio, 10.

Figure 12. - Concluded. Effect of fan pressure ratio and duct-outlet air temperature T_3' on required reactor heat release per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; any duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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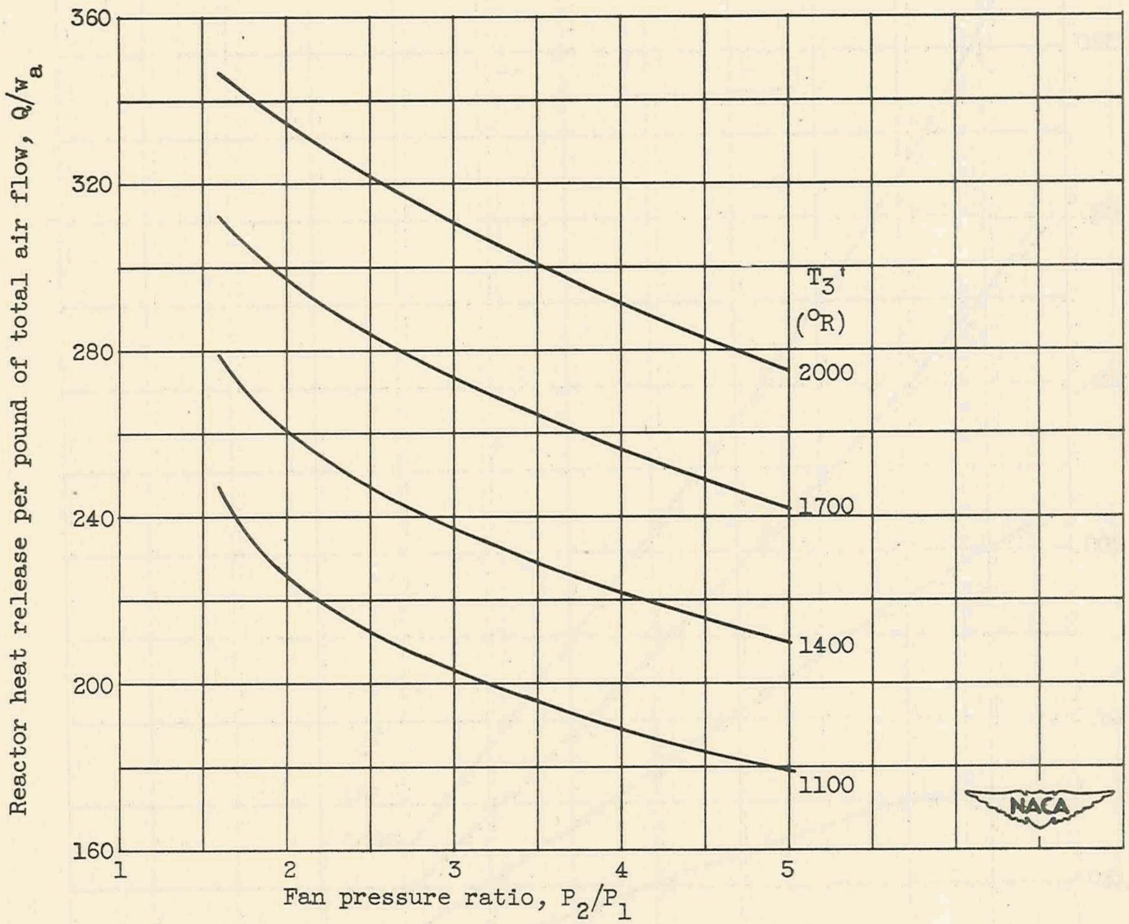

(a) Compressor pressure ratio, 1.

Figure 13. - Effect of fan pressure ratio and duct-outlet air temperature T_3' on required reactor heat release per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; any duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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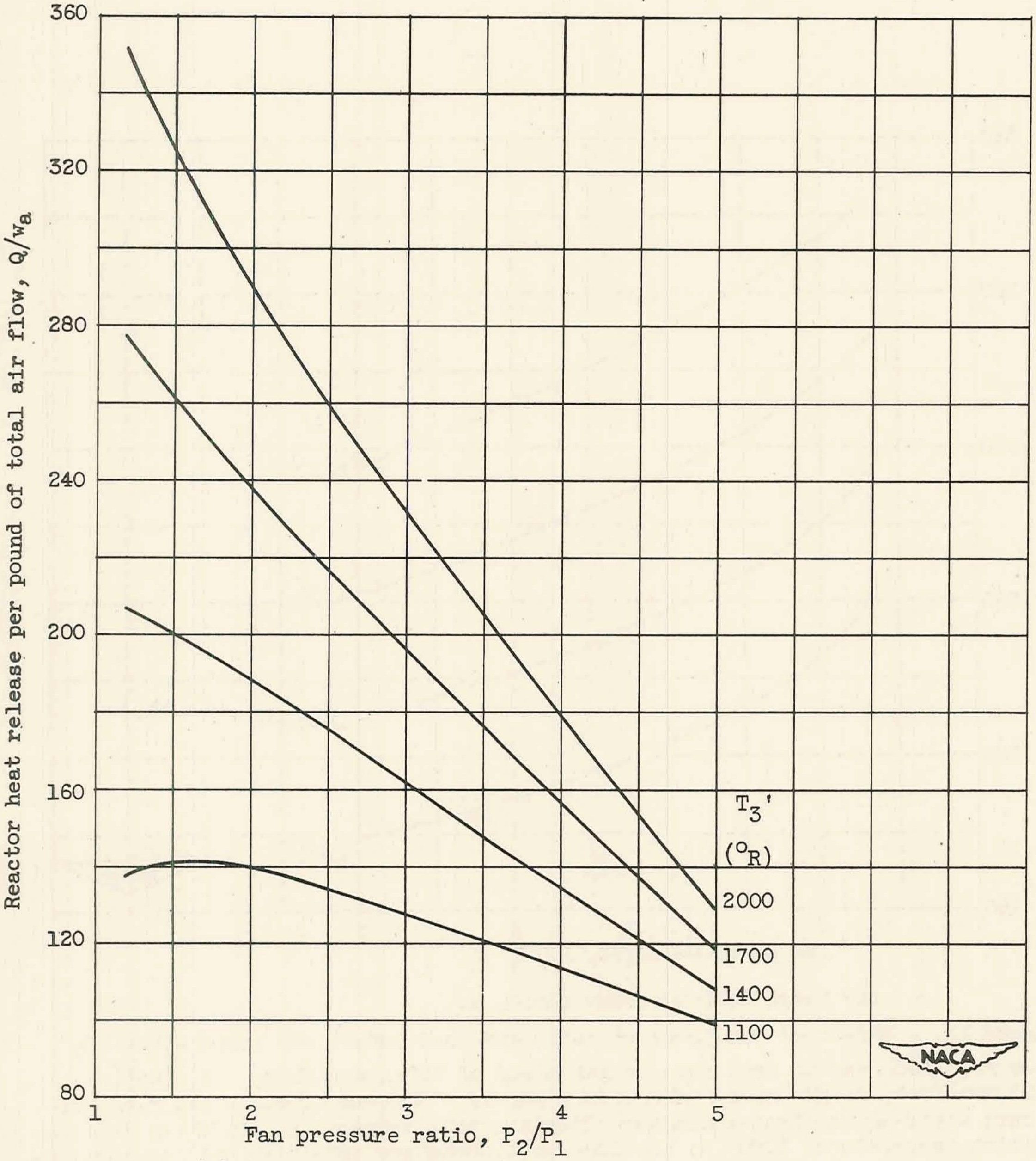

(b) Compressor pressure ratio, 5.

Figure 13. - Continued. Effect of fan pressure ratio and duct-outlet air temperature T_3' on required reactor heat release per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; any duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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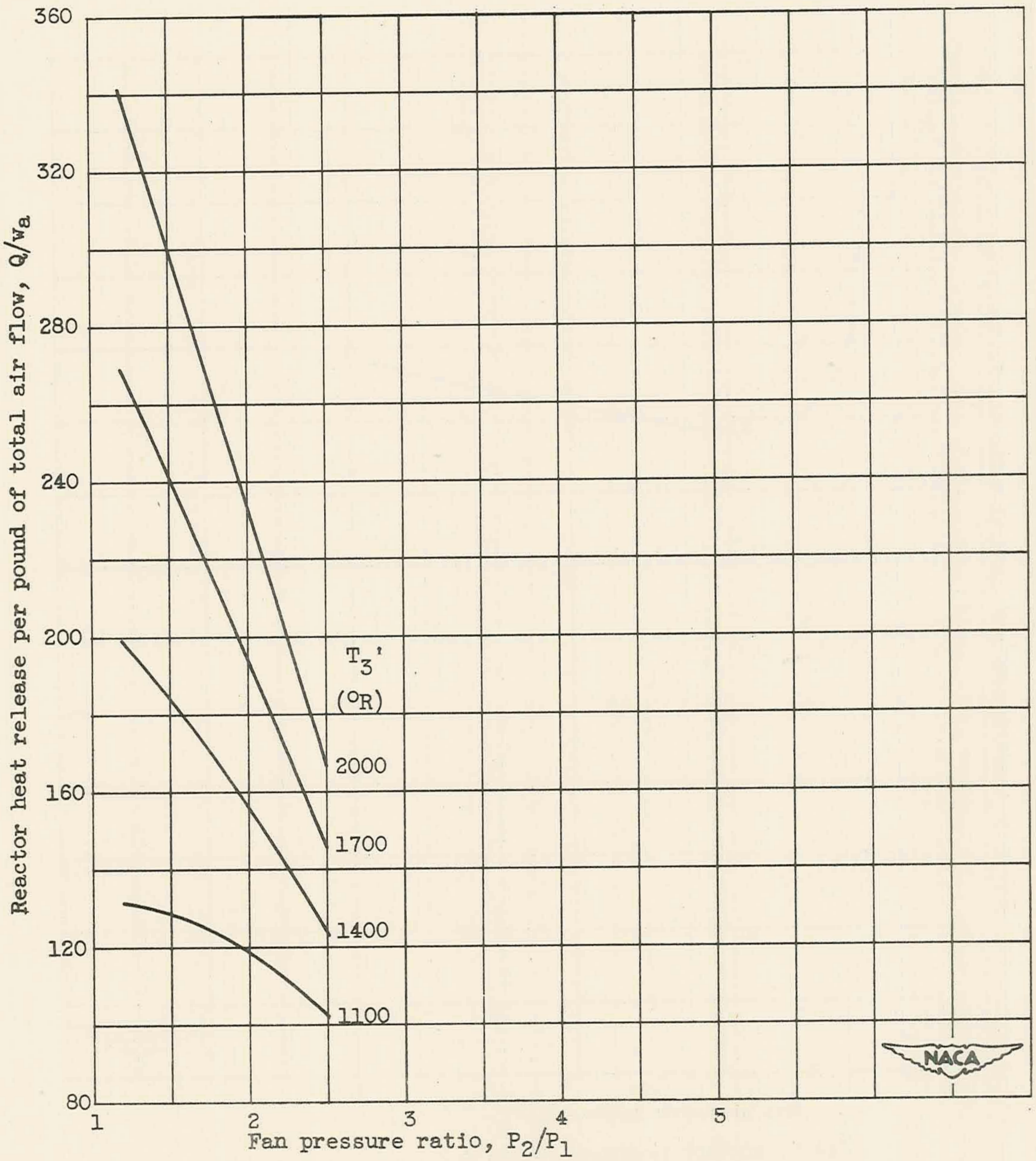

(c) Compressor pressure ratio, 10.

Figure 13. - Concluded. Effect of fan pressure ratio and duct-outlet air temperature T_3' on required reactor heat release per pound of total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; any duct heat-exchanger inlet Mach number; basic-engine heat-exchanger effective wall temperature, 2270^{o} R; turbine-inlet temperature, 2000^{o} R; any duct heat-exchanger effective wall temperature.

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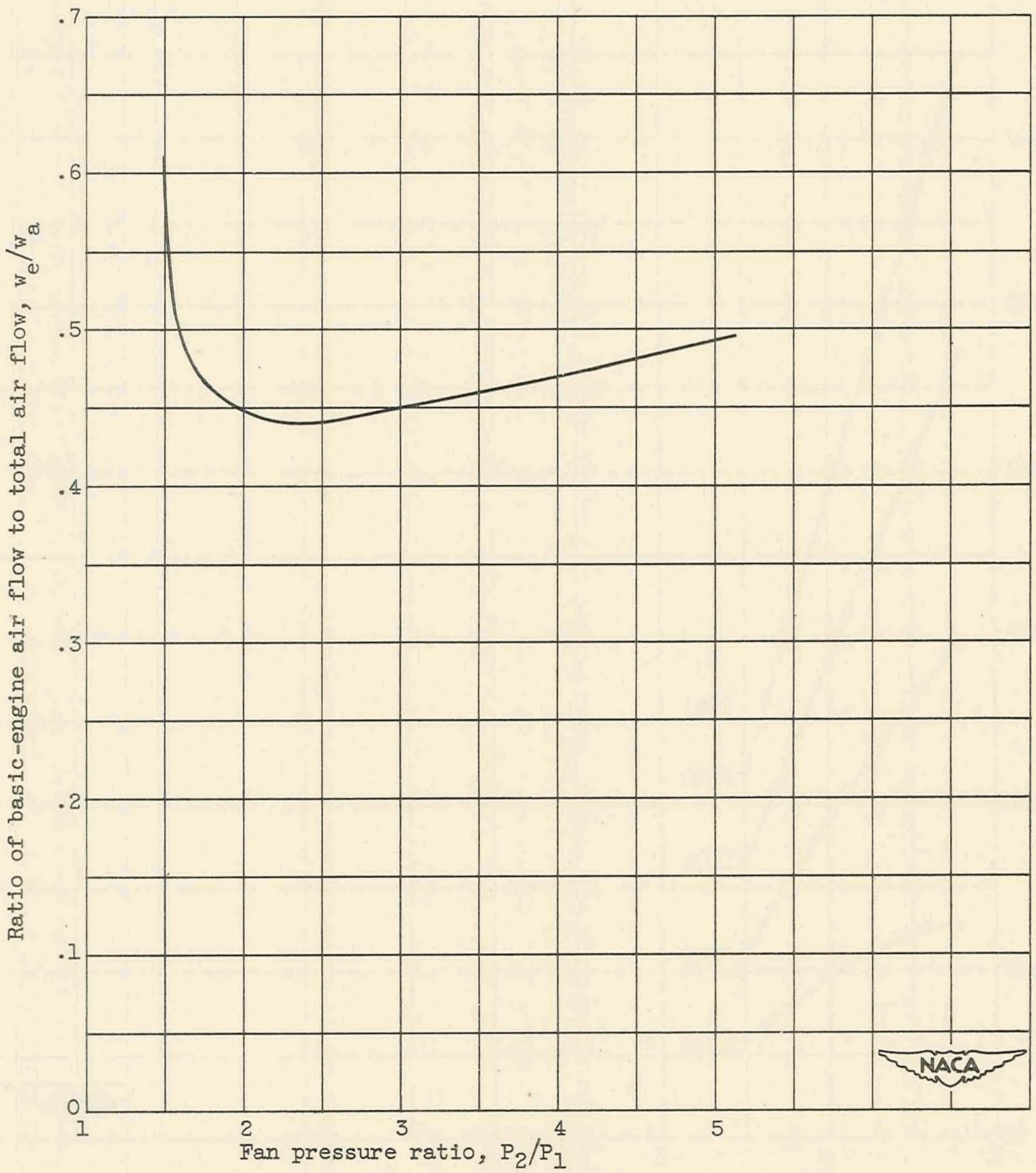

(a) Compressor pressure ratio, 1.

Figure 14. - Effect of fan pressure ratio on ratio of basic-engine air flow to total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; any duct heat-exchanger inlet Mach number; any duct-outlet air temperature; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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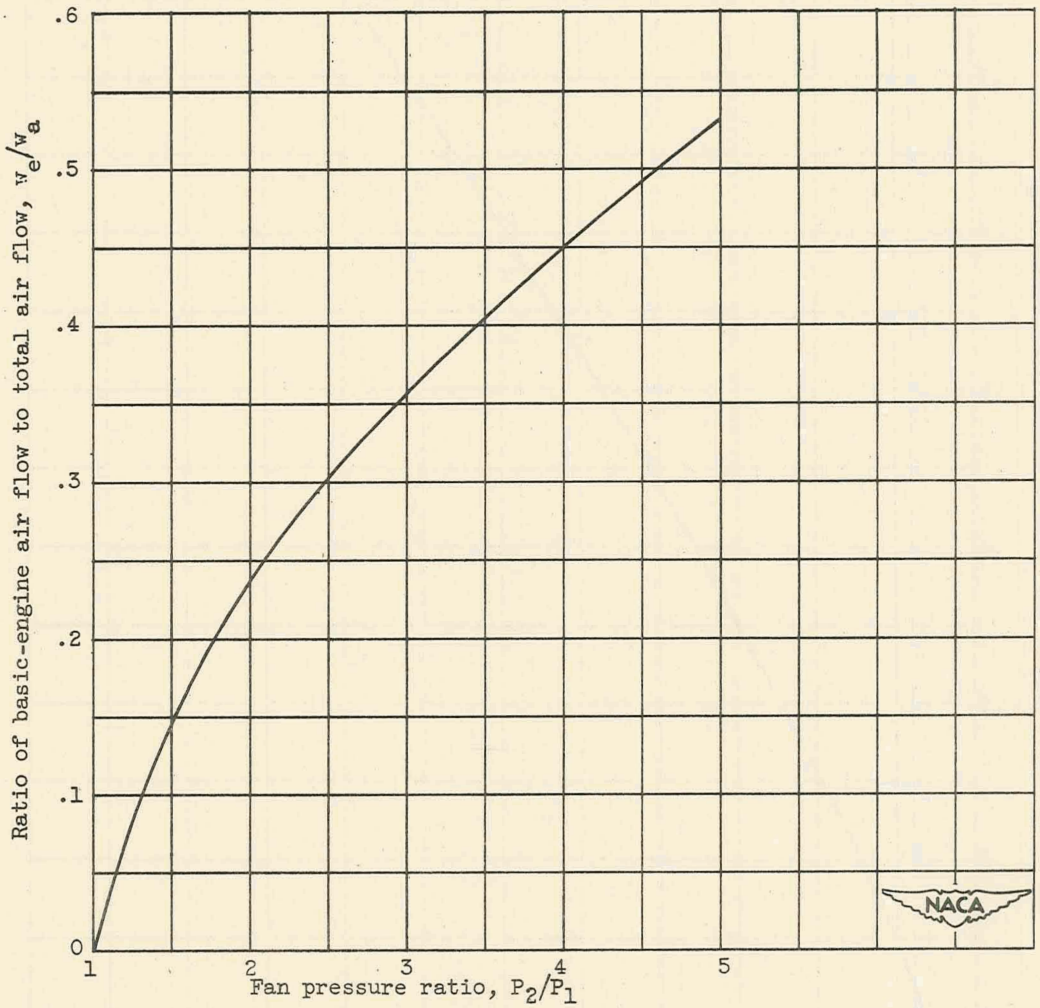

(b) Compressor pressure ratio, 5.

Figure 14. - Continued. Effect of fan pressure ratio on ratio of basic-engine air flow to total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; any duct heat-exchanger inlet Mach number; any duct-outlet air temperature; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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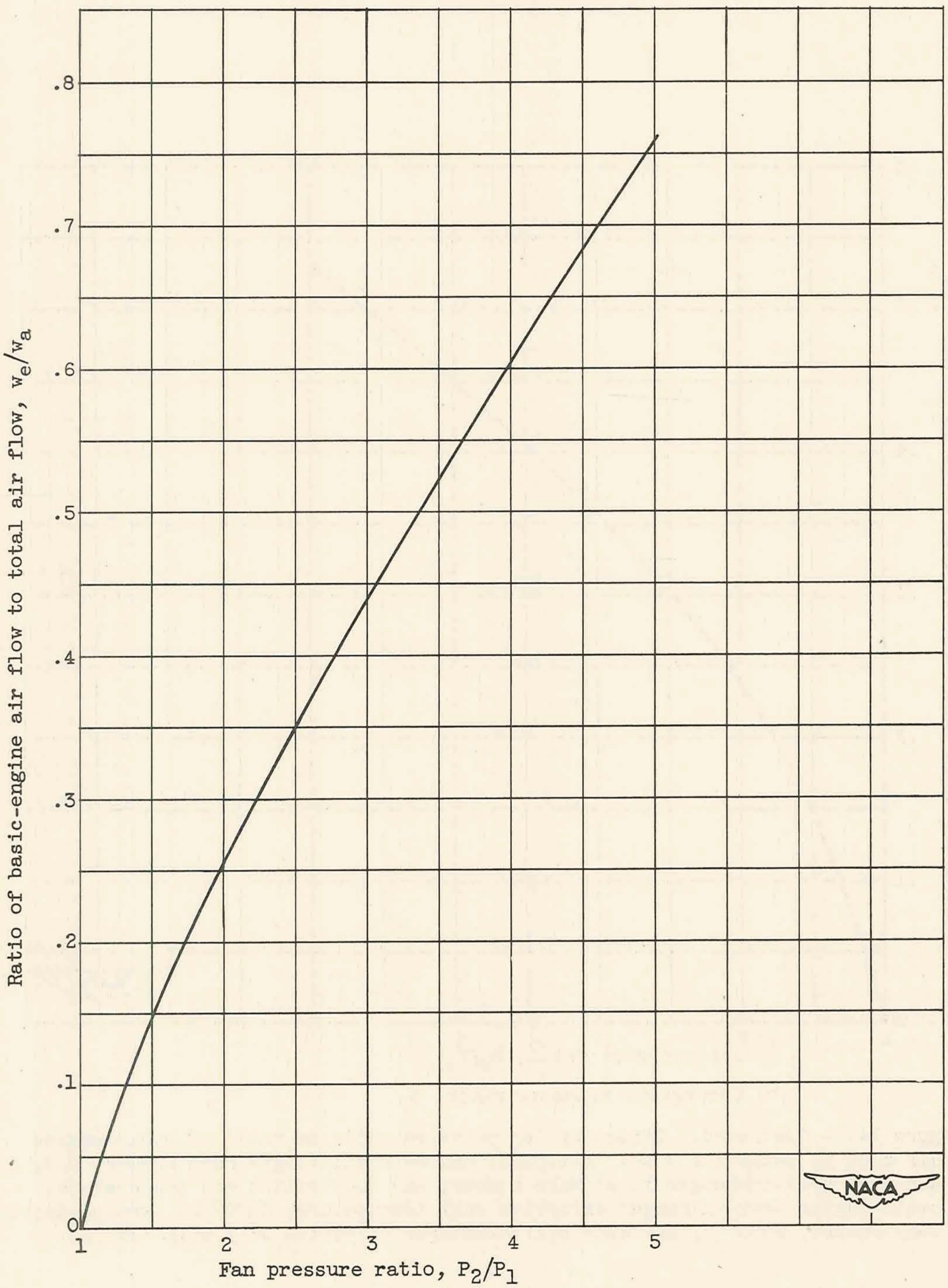

(c) Compressor pressure ratio, 10.

Figure 14. - Concluded. Effect of fan pressure ratio on ratio of basic-engine air flow to total air flow. Altitude, 50,000 feet; flight Mach number, 0.9; any duct heat-exchanger inlet Mach number; any duct-outlet air temperature; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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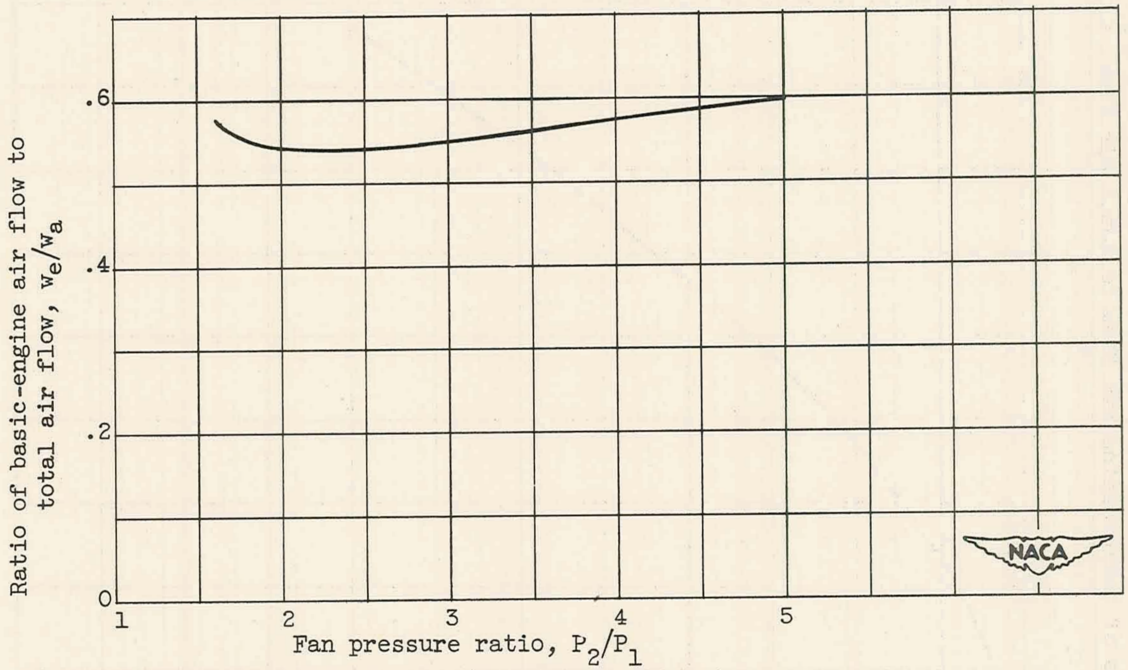

(a) Compressor pressure ratio, 1.

Figure 15. - Effect of fan pressure ratio on ratio of basic engine air flow to total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; any duct heat-exchanger inlet Mach number; any duct-outlet air temperature; basic-engine heat exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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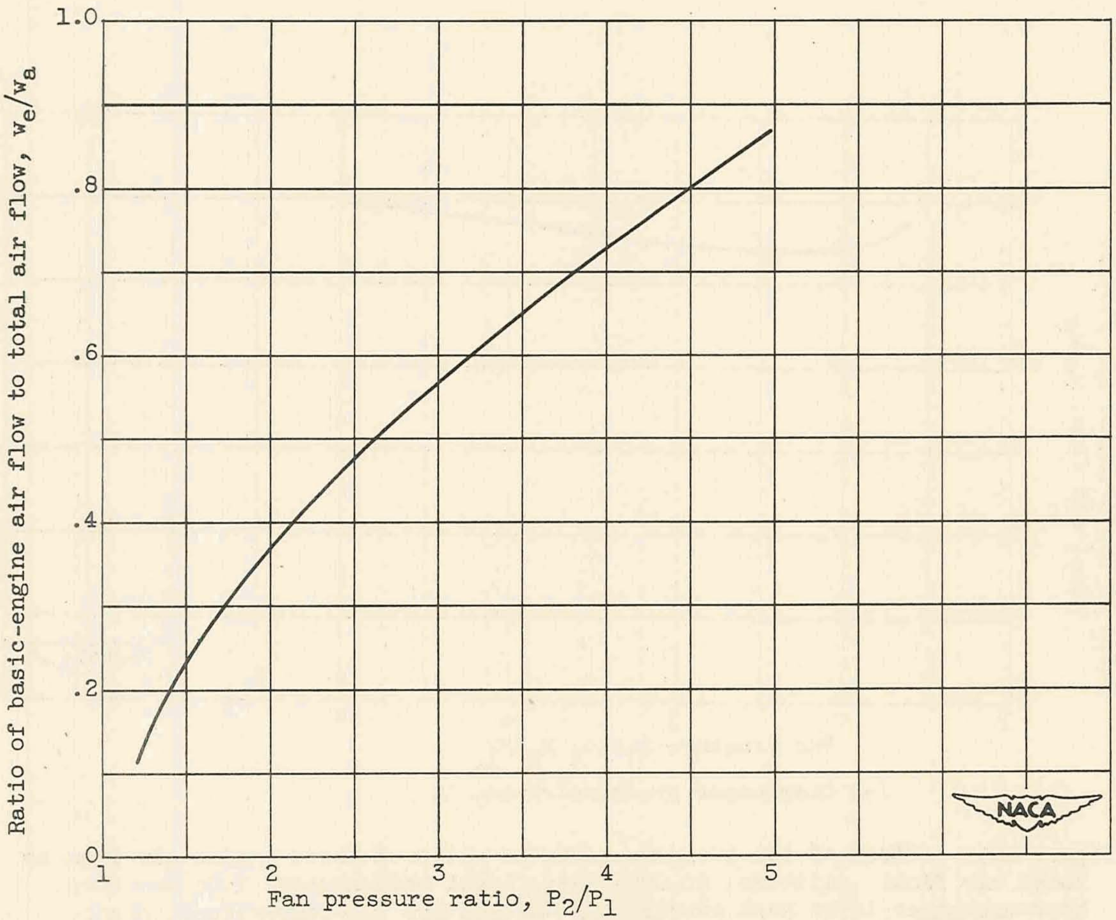

(b) Compressor pressure ratio, 5.

Figure 15. - Continued. Effect of fan pressure ratio on ratio of basic-engine air flow to total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; any duct heat-exchanger inlet Mach number; any duct-outlet air temperature; 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.

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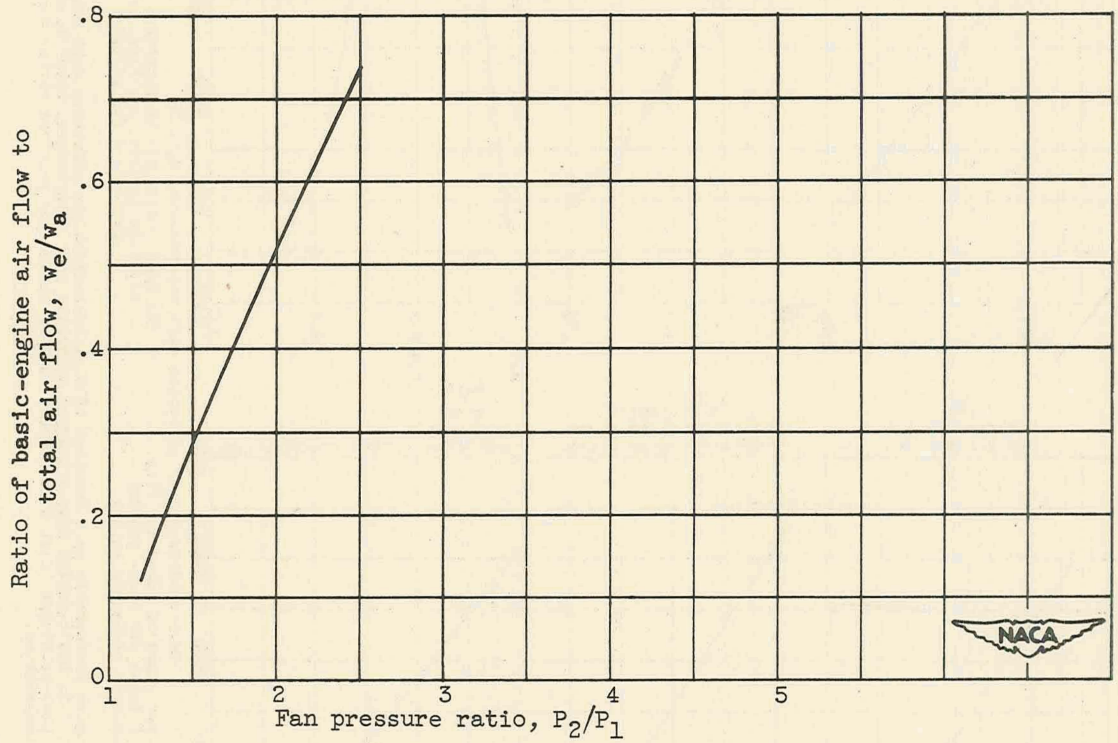
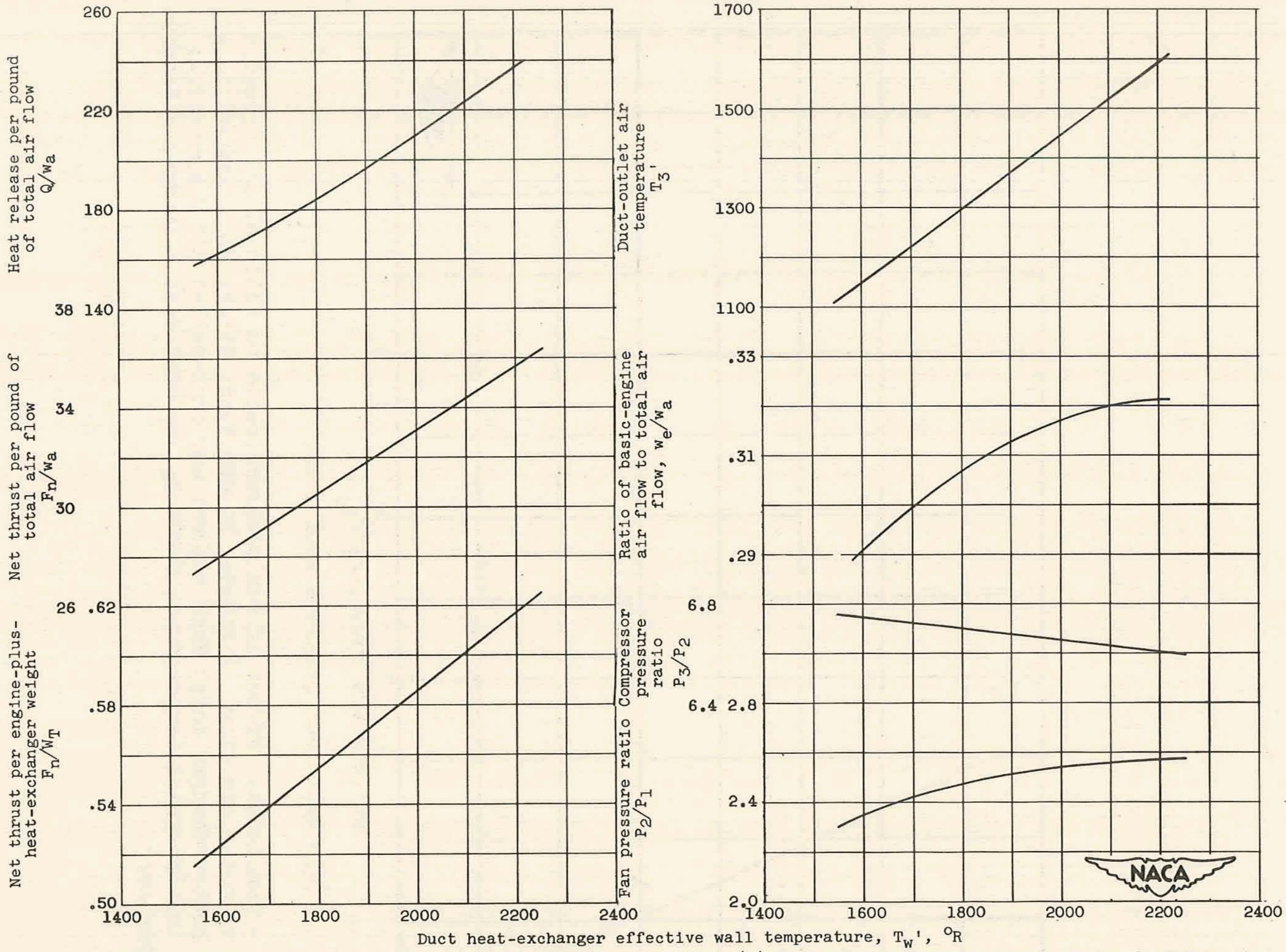


(c) Compressor pressure ratio, 10.

Figure 15. - Concluded. Effect of fan pressure ratio on ratio of basic-engine air flow to total air flow. Altitude, 50,000 feet; flight Mach number, 1.5; any duct heat-exchanger inlet Mach number; any duct-outlet air temperature; 2270° R; turbine-inlet temperature, 2000° R; any duct heat-exchanger effective wall temperature.



(a) Reactor heat release per pound of total air flow, net thrust per pound of total air flow; and net thrust per engine-plus-heat exchanger weight.

(b) Duct-outlet air temperature, ratio of basic-engine air flow to total air flow, compressor pressure ratio, and fan pressure ratio.

Figure 16. - Optimum ducted-fan engine performance as a function of duct heat-exchanger effective wall temperature. Altitude, 50,000 feet; flight Mach number, 0.9; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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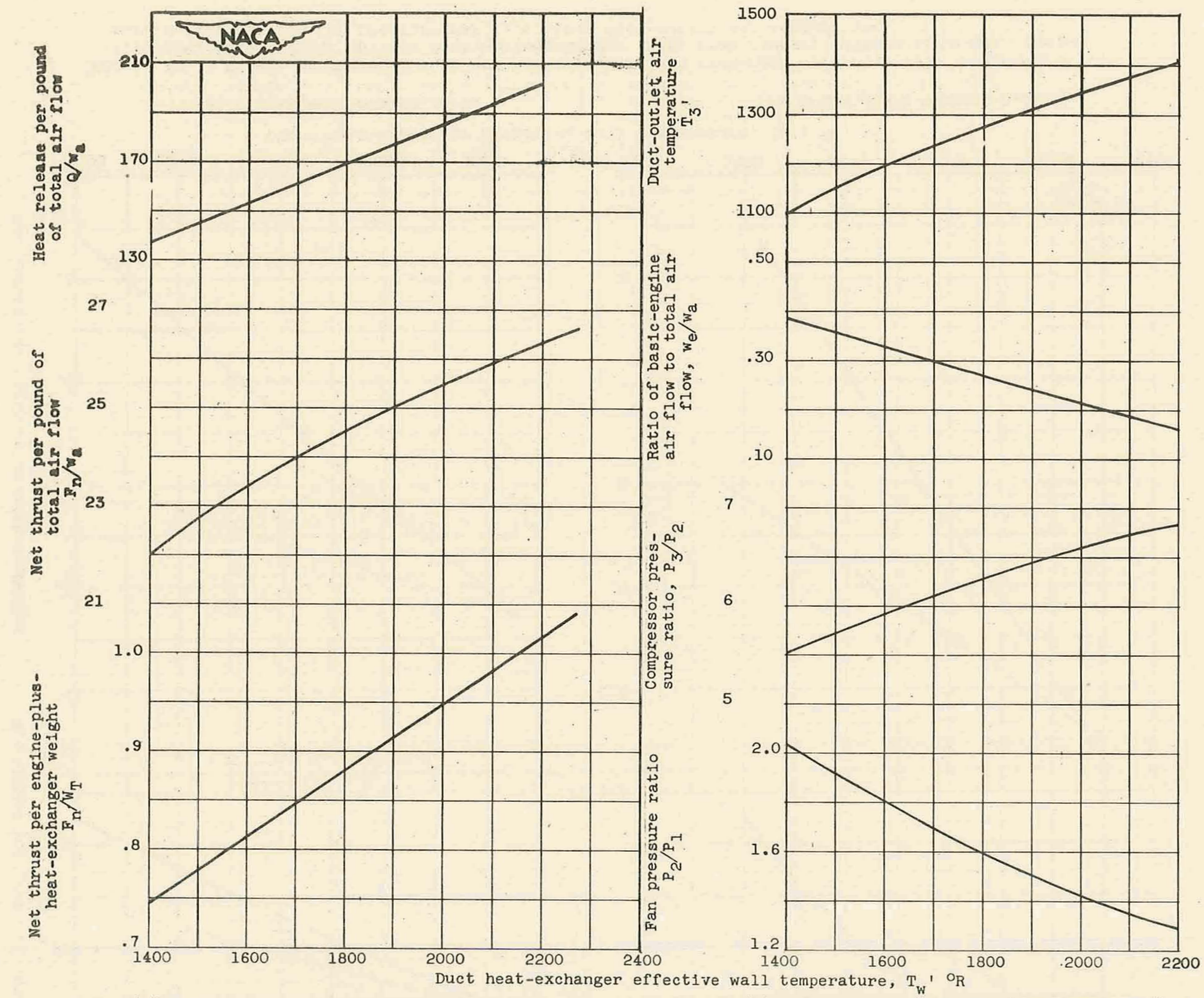

(a) Reactor heat release per pound of total air flow, net thrust per pound of total air flow; and net thrust per engine-plus-heat exchanger weight.

(b) Duct-outlet air temperature, ratio of basic-engine air flow to total air flow, compressor pressure ratio, and fan pressure ratio.

Figure 17. - Optimum ducted-fan engine performance as a function of duct-heat exchanger effective wall temperature. Altitude, 50,000 feet; flight Mach number, 1.5; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; optimum fan pressure ratio; optimum duct-outlet air temperature.

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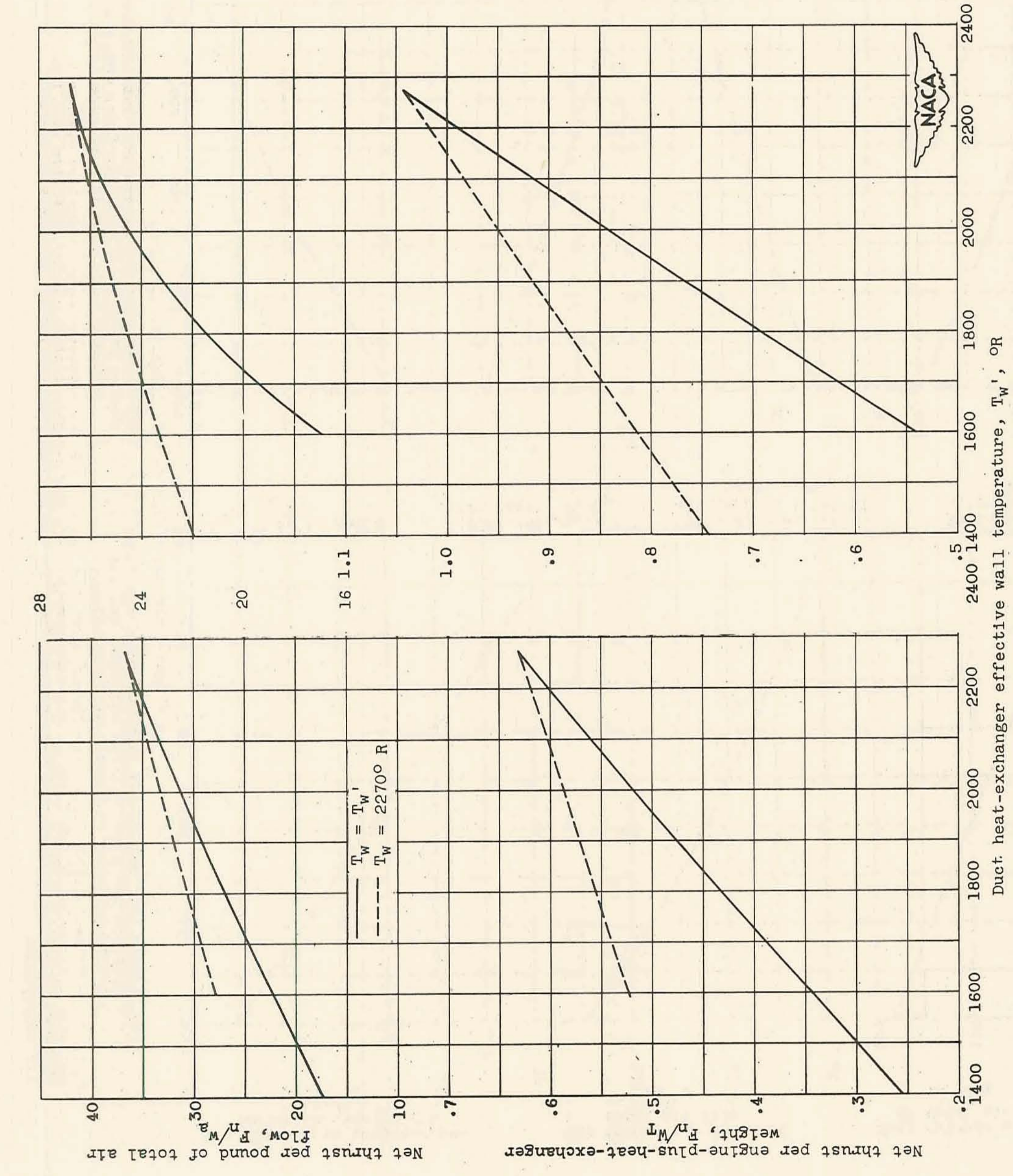
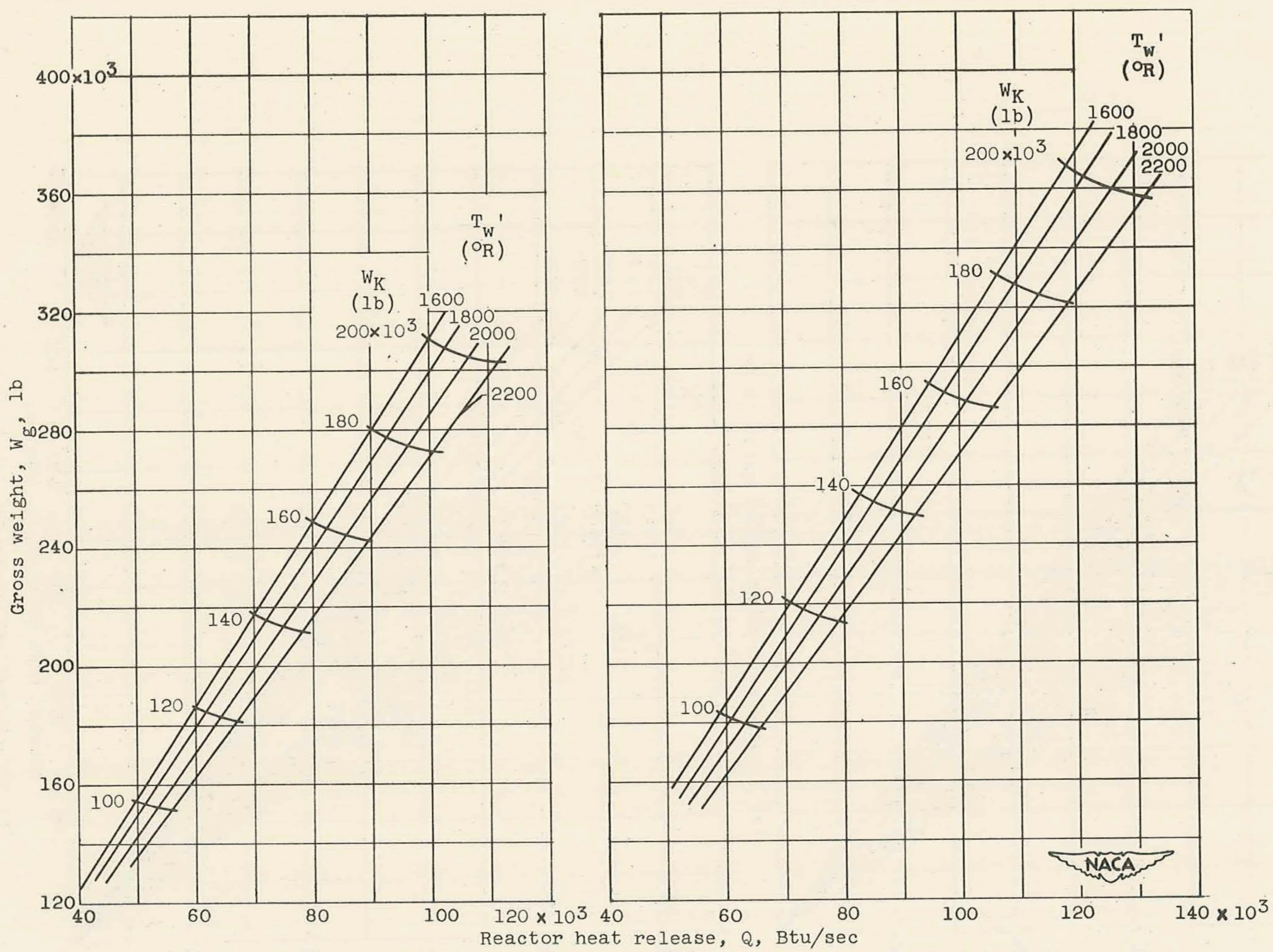


(a) Flight Mach number, 0.9.

(b) Flight Mach number, 1.5.

Figure 18. - Effect of reducing duct and basic-engine heat exchanger effective wall temperature. Altitude, 50,000 feet; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.



(a) Structure-to-gross-weight ratio, 0.25.

(b) Structure-to-gross-weight ratio, 0.35.

Figure 19. - Airplane gross weight and reactor heat release as a function of duct heat-exchanger effective wall temperature T_W' and reactor-plus-shield-plus-payload-plus-auxiliary weight W_K. Altitude, 50,000 feet; flight Mach number, 0.9; lift-drag ratio, 18; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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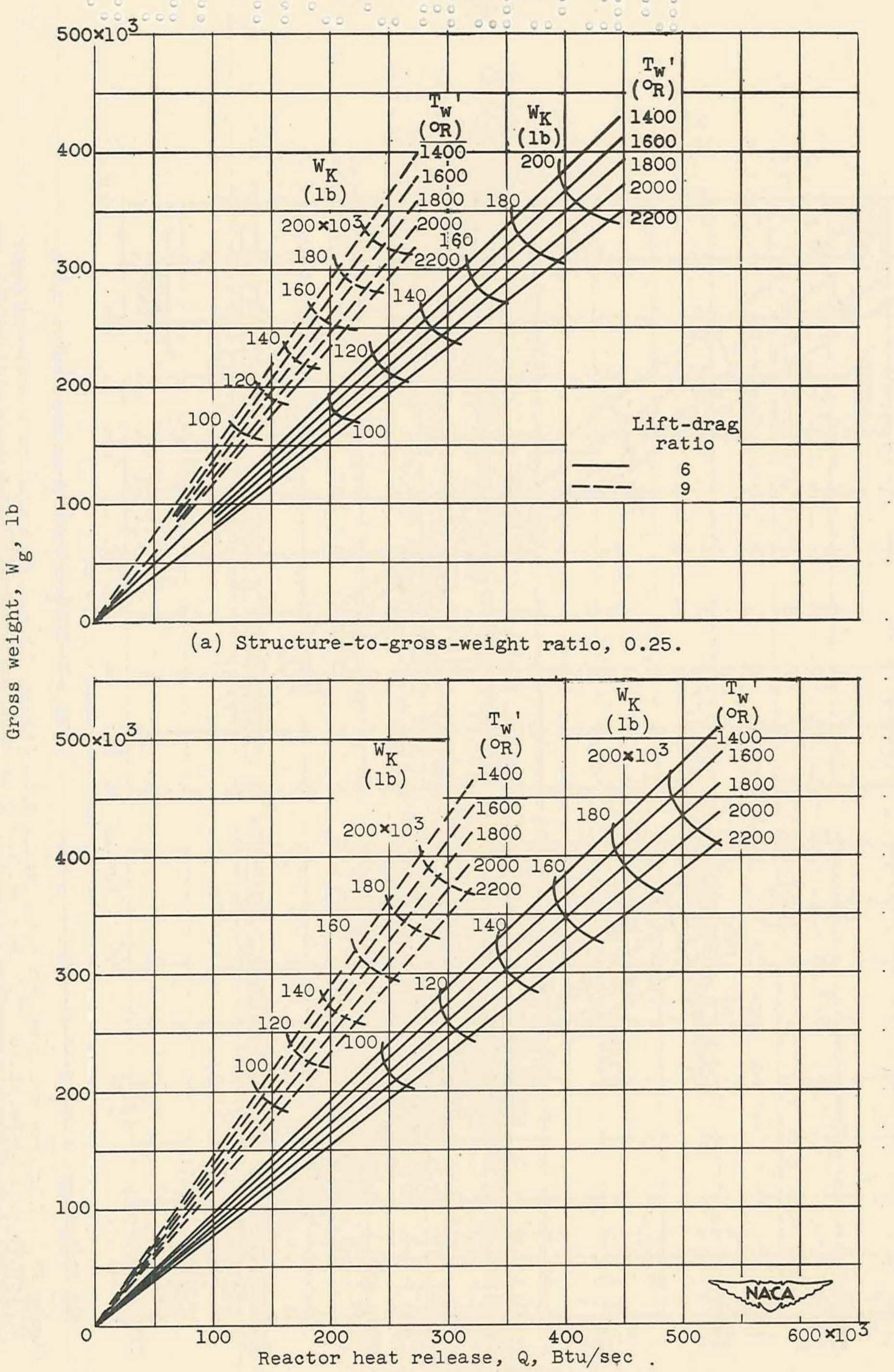

(a) Structure-to-gross-weight ratio, 0.25.

(b) Structure-to-gross-weight ratio, 0.35.

Figure 20. - Airplane gross weight and reactor heat release as a function of duct heat-exchanger wall temperature T_W' and reactor-plus-shield-plus-payload-plus-auxiliary weight W_K. Altitude, 50,000 feet; flight Mach number, 1.5; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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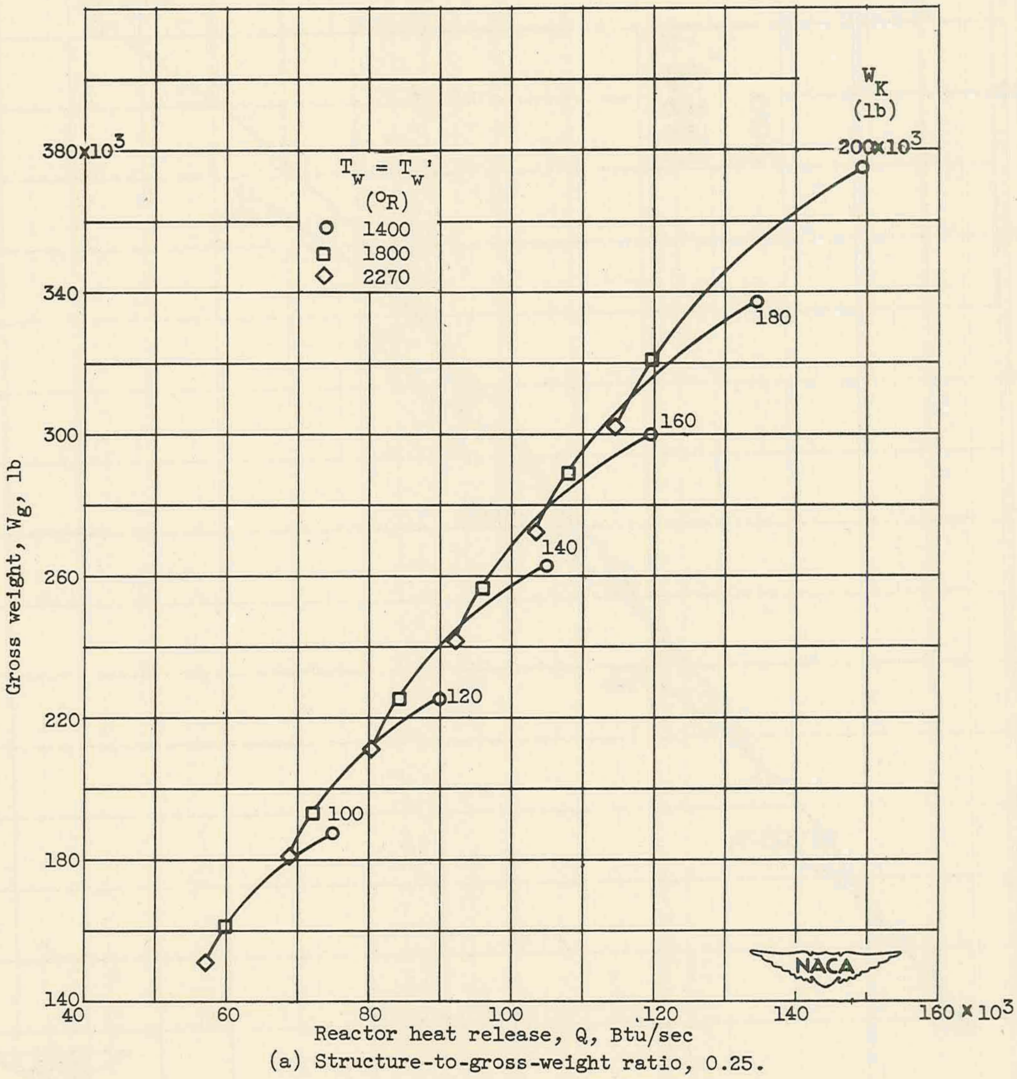

(a) Structure-to-gross-weight ratio, 0.25.

Figure 21. - Airplane gross weight and reactor heat release at reduced basic-engine heat-exchanger effective wall temperature T_w. Altitude, 50,000 feet; flight Mach number, 0.9; airplane lift-drag ratio, 18; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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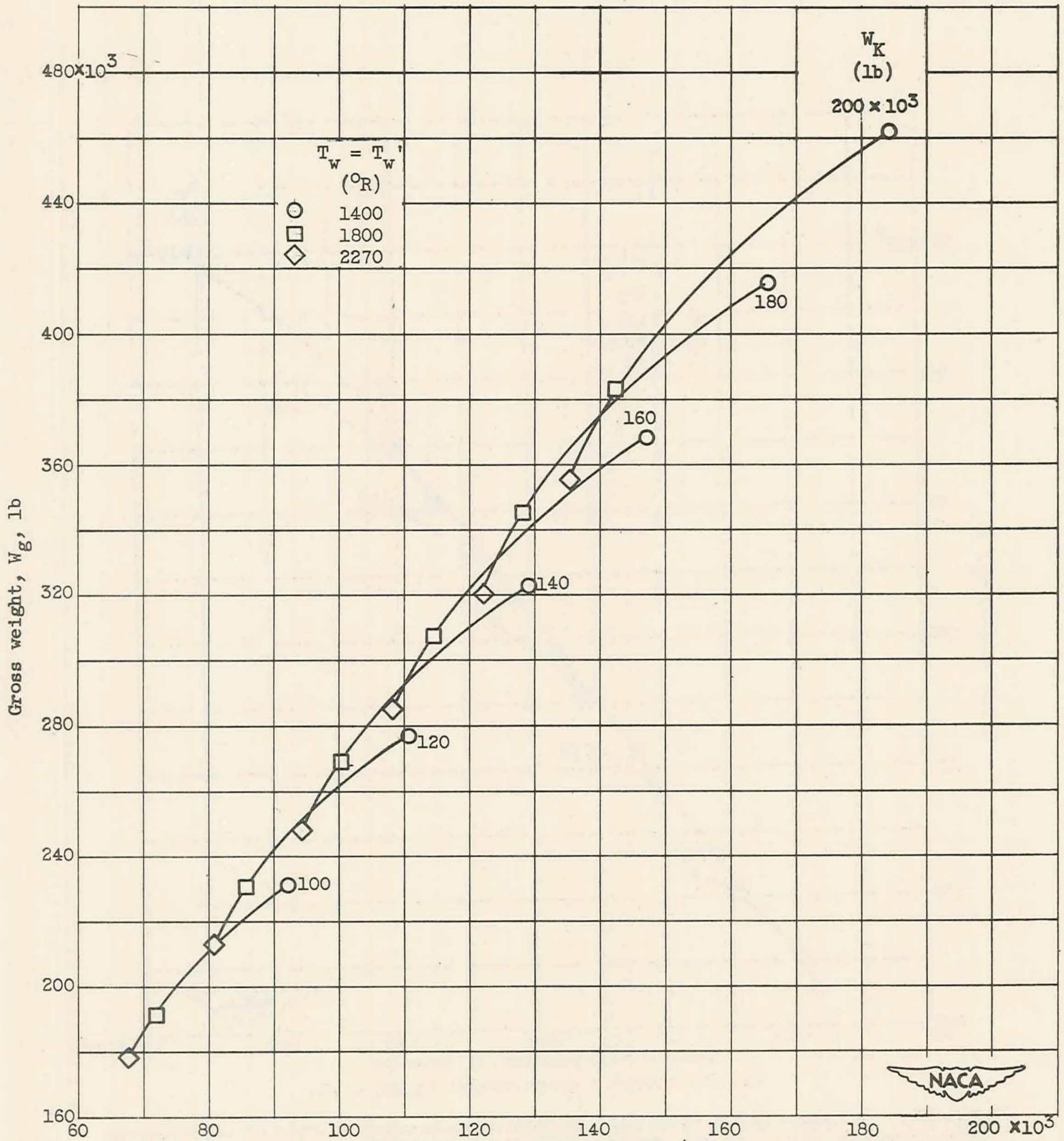

(b) Structure-to-gross weight ratio, 0.35.

Figure 21. - Concluded. Airplane gross weight and reactor heat release at reduced basic-engine heat-exchanger effective wall temperature T_w. Altitude, 50,000 feet; flight Mach number, 0.9; airplane lift-drag ratio, 18; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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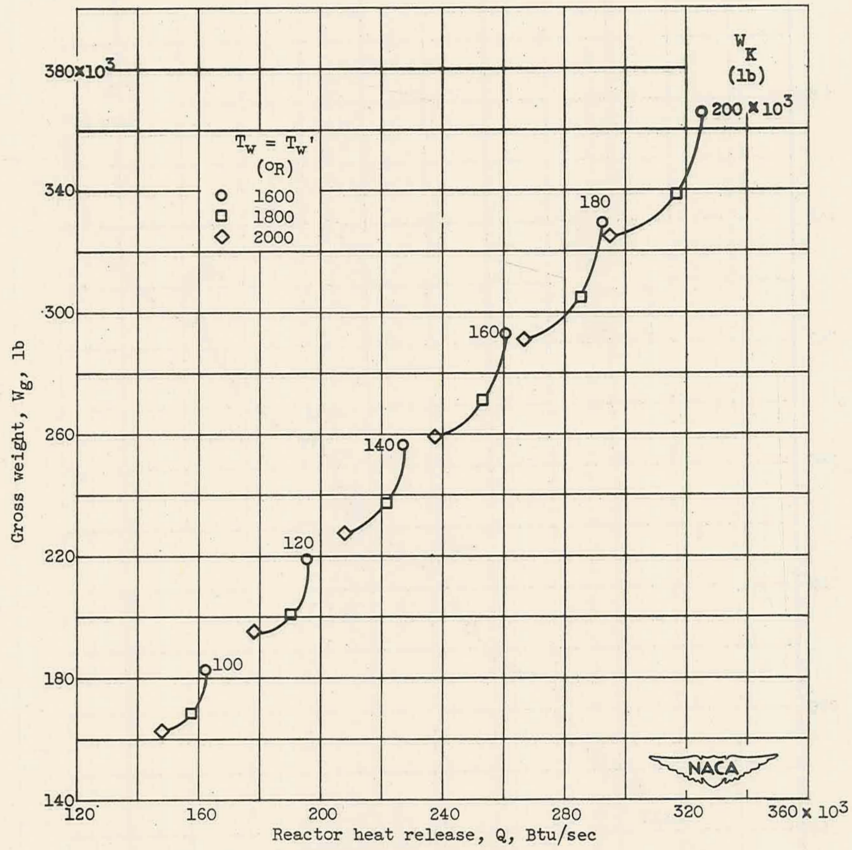

(a) Structure-to-gross-weight ratio, 0.25; lift-drag ratio, 9.

Figure 22. - Airplane gross weight and reactor heat release at reduced basic-engine heat-exchanger effective wall temperature T_w. Altitude, 50,000 feet; flight Mach number, 1.5; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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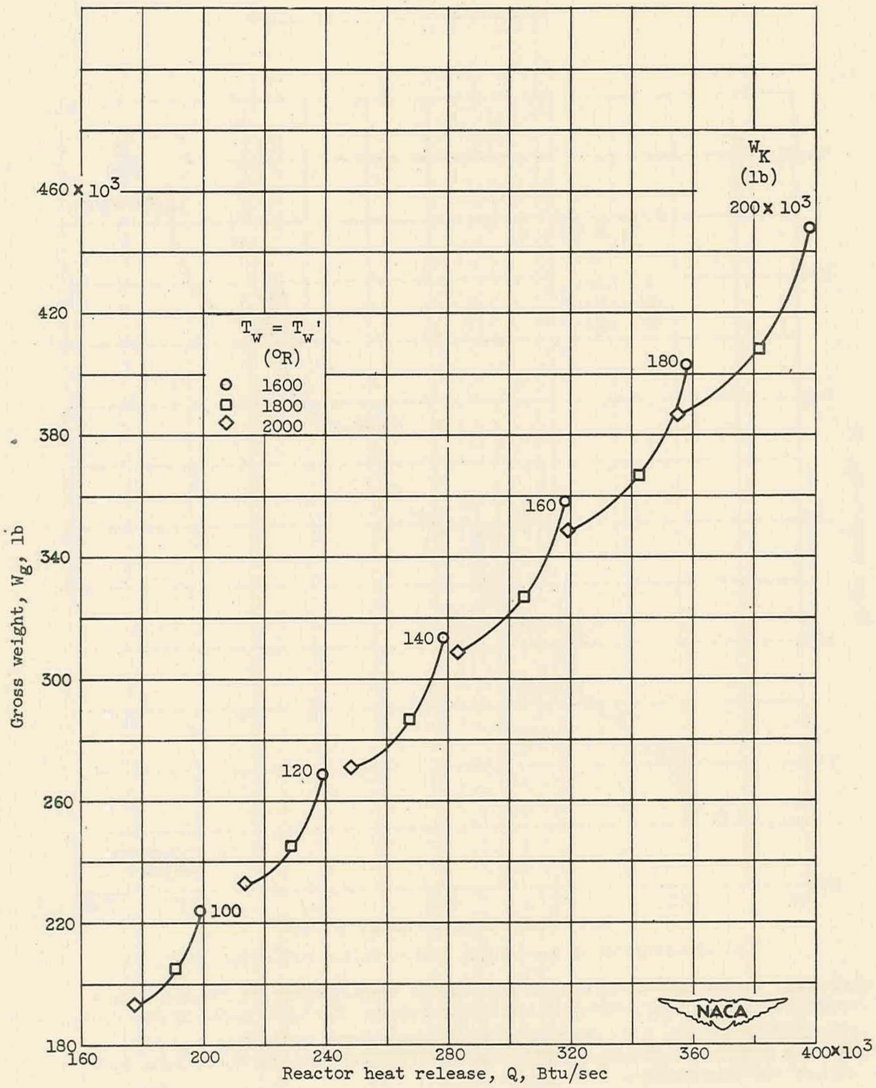

(b) Structure-to-gross-weight ratio, 0.35; lift-drag ratio, 9.

Figure 22. - Continued. Airplane gross weight and reactor heat release at reduced basic-engine heat-exchanger wall temperature T_w. Altitude, 50,000 feet; flight Mach number, 1.5; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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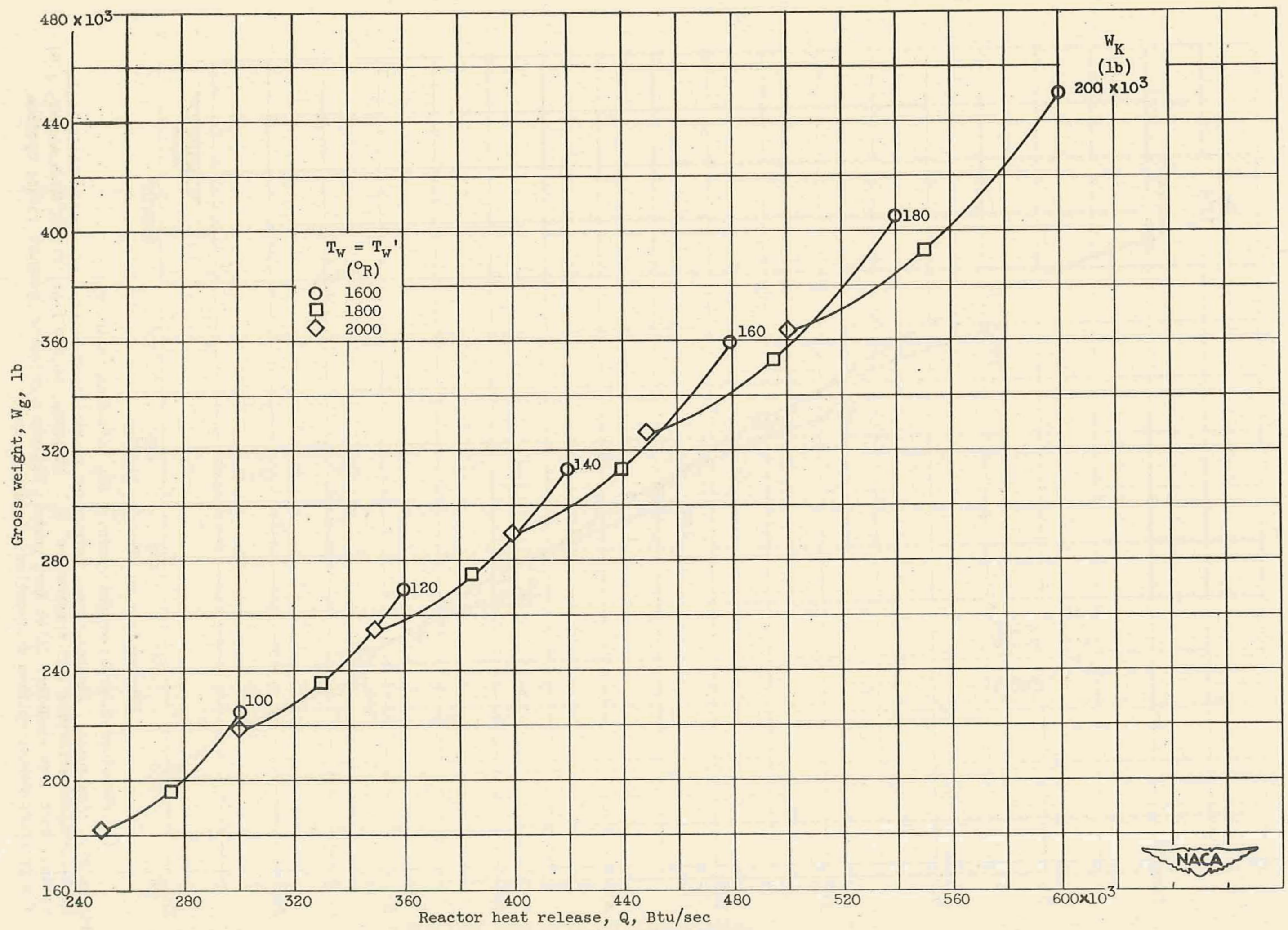

(c) Structure-to-gross-weight ratio, 0.25; lift-drag ratio, 6.

Figure 22. - Continued. Airplane gross weight and reactor heat release at reduced basic-engine heat-exchanger effective wall temperature T_w. Altitude, 50,000 feet; flight Mach number, 1.5; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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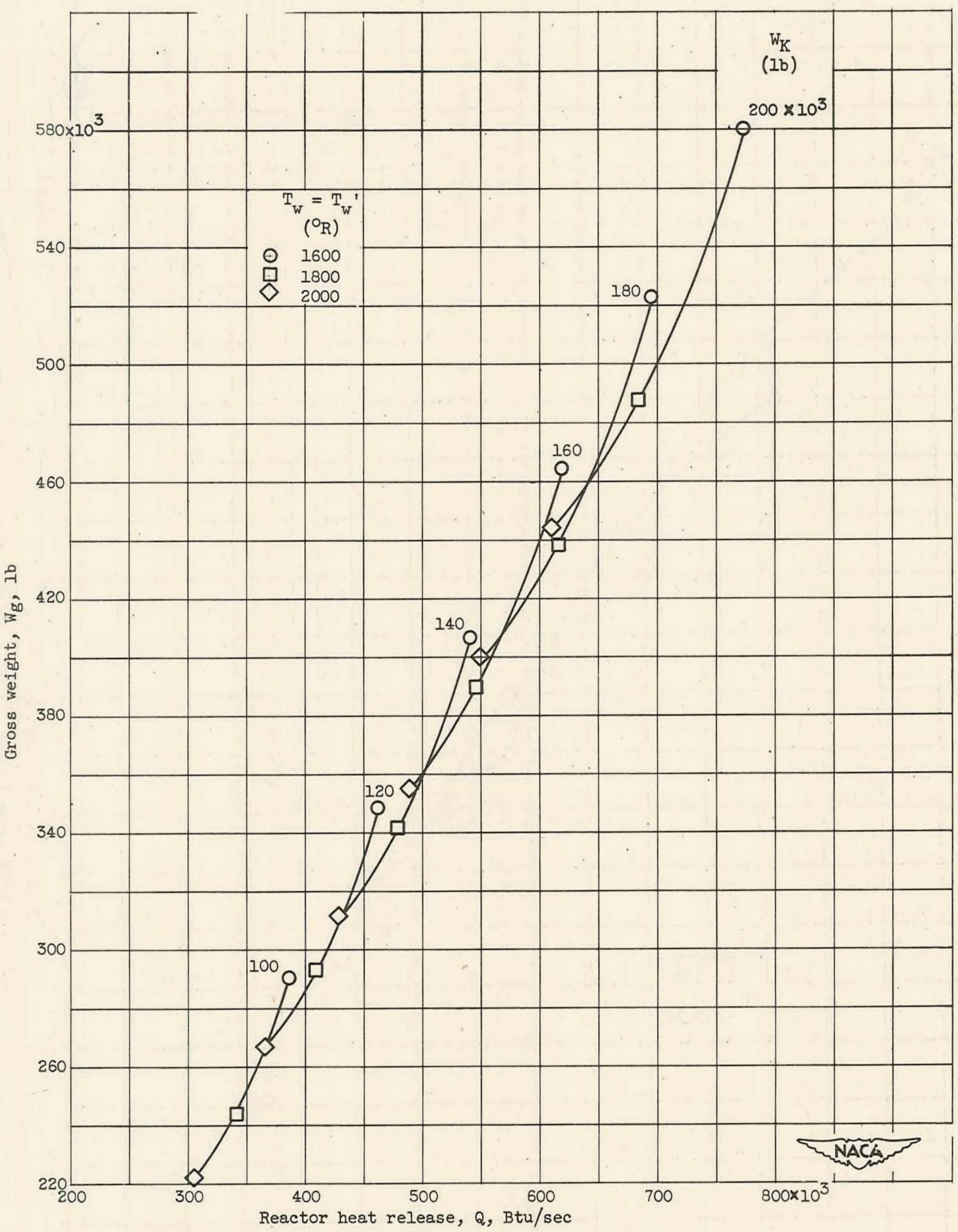

(d) Structure-to-gross-weight ratio, 0.35; lift-drag ratio, 6

Figure 22. - Concluded. Airplane gross weight and reactor heat release at reduced basic-engine heat-exchanger effective wall temperature T_w. Altitude, 50,000 feet; flight Mach number, 1.5; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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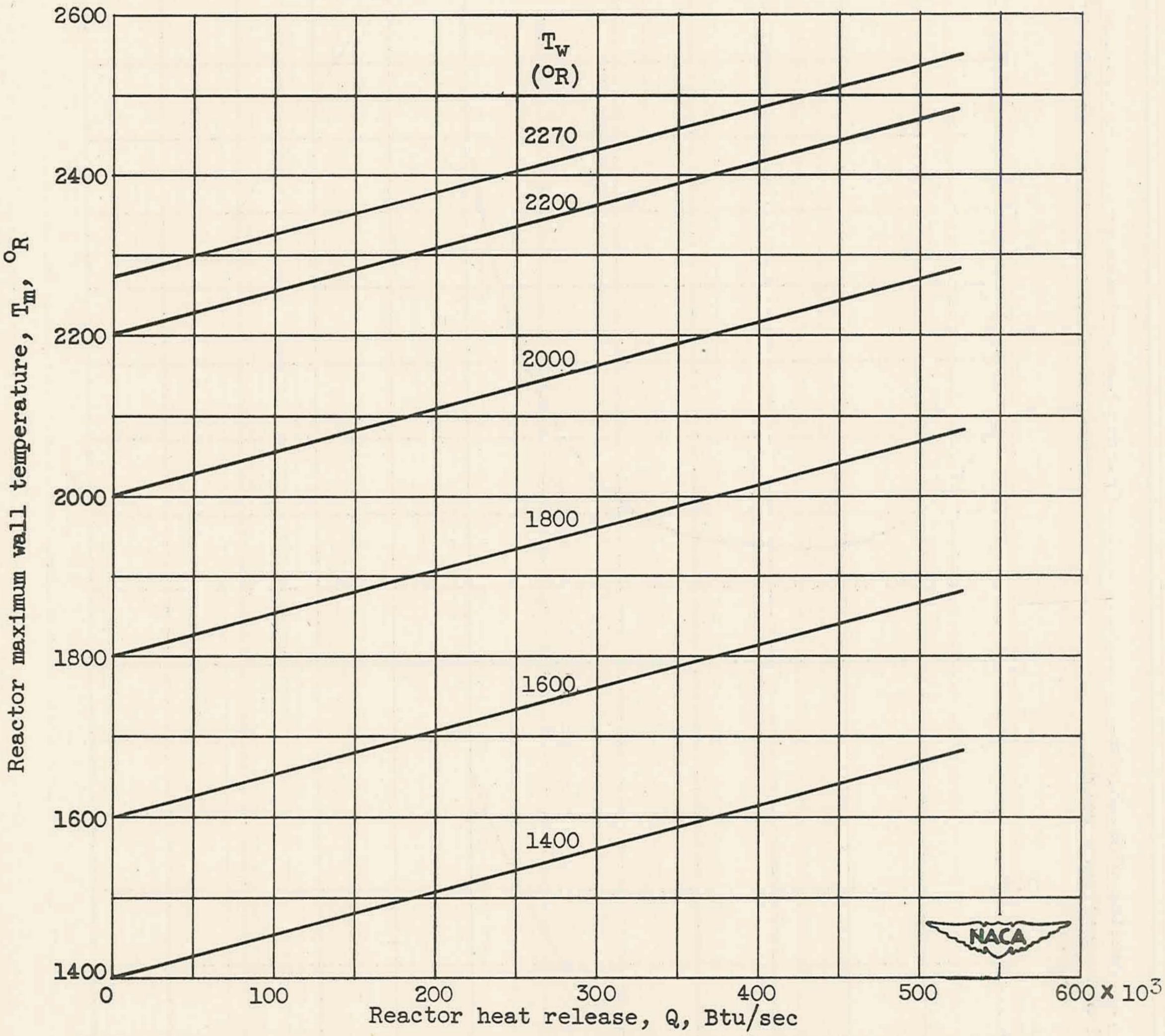

Figure 23. - Reactor maximum wall temperatures as a function of basic-engine heat-exchanger effective wall temperature T_W and reactor heat release.

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(a) Flight Mach number, 0.9; lift-drag ratio, 18.

Figure 24. - Effect of altitude on airplane gross weight and reactor heat release per reactor-plus-shield-plus-payload-plus-auxiliary weight. Structure-to-gross-weight ratio, 0.35; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger wall temperature, 1800° R; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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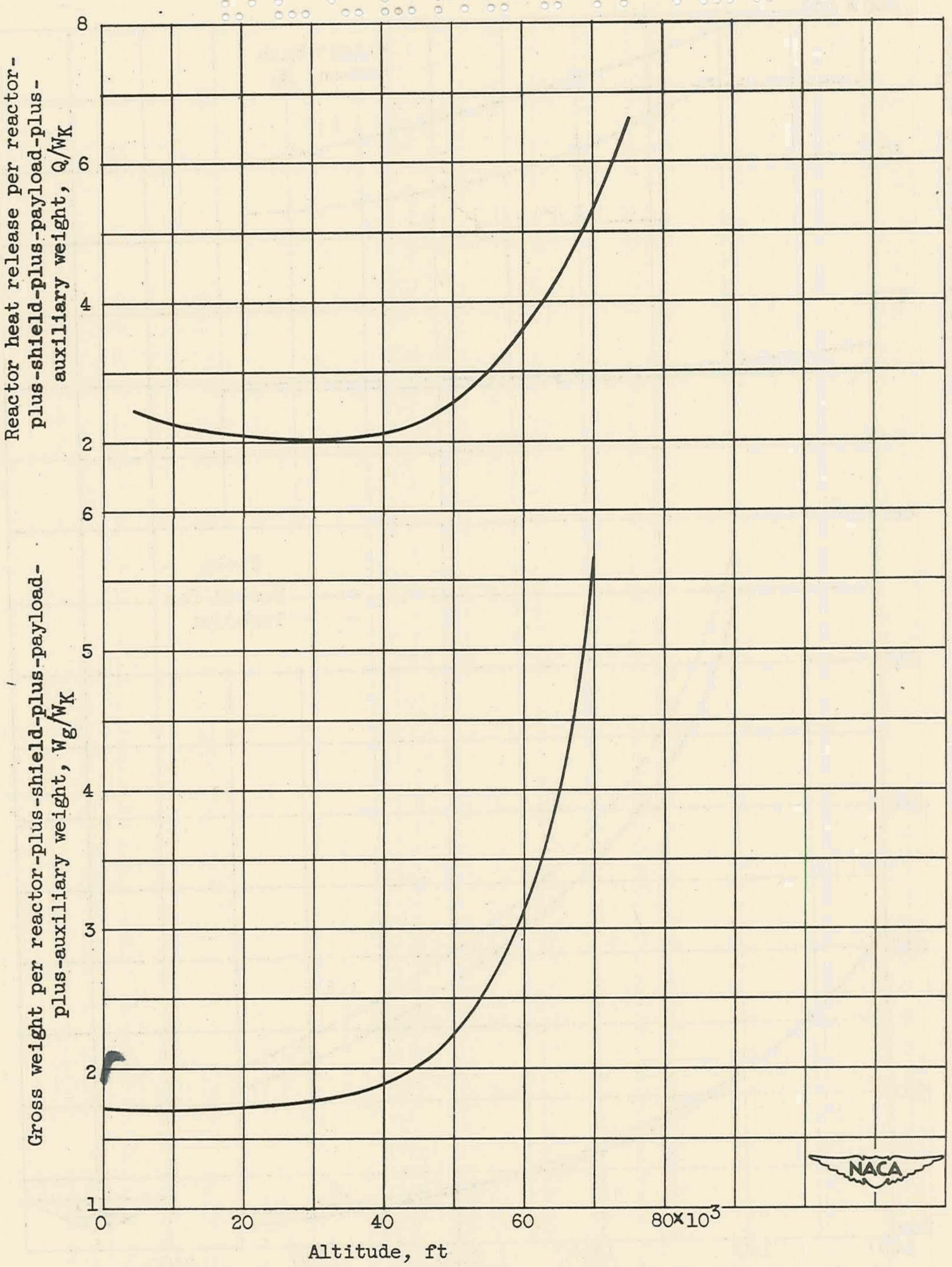

(b) Flight Mach number, 1.5; lift-drag ratio, 6.

Figure 24. - Concluded. Effect of altitude on airplane gross weight and reactor heat release per reactor-plus-shield-plus-payload-plus-auxiliary weight. Structure-to-gross-weight ratio, 0.35; basic-engine heat-exchanger effective wall temperature, 2270° R; turbine-inlet temperature, 2000° R; duct heat-exchanger wall temperature, 1800° R; optimum duct heat-exchanger inlet Mach number; optimum compressor pressure ratio; optimum fan pressure ratio; optimum duct-outlet air temperature.

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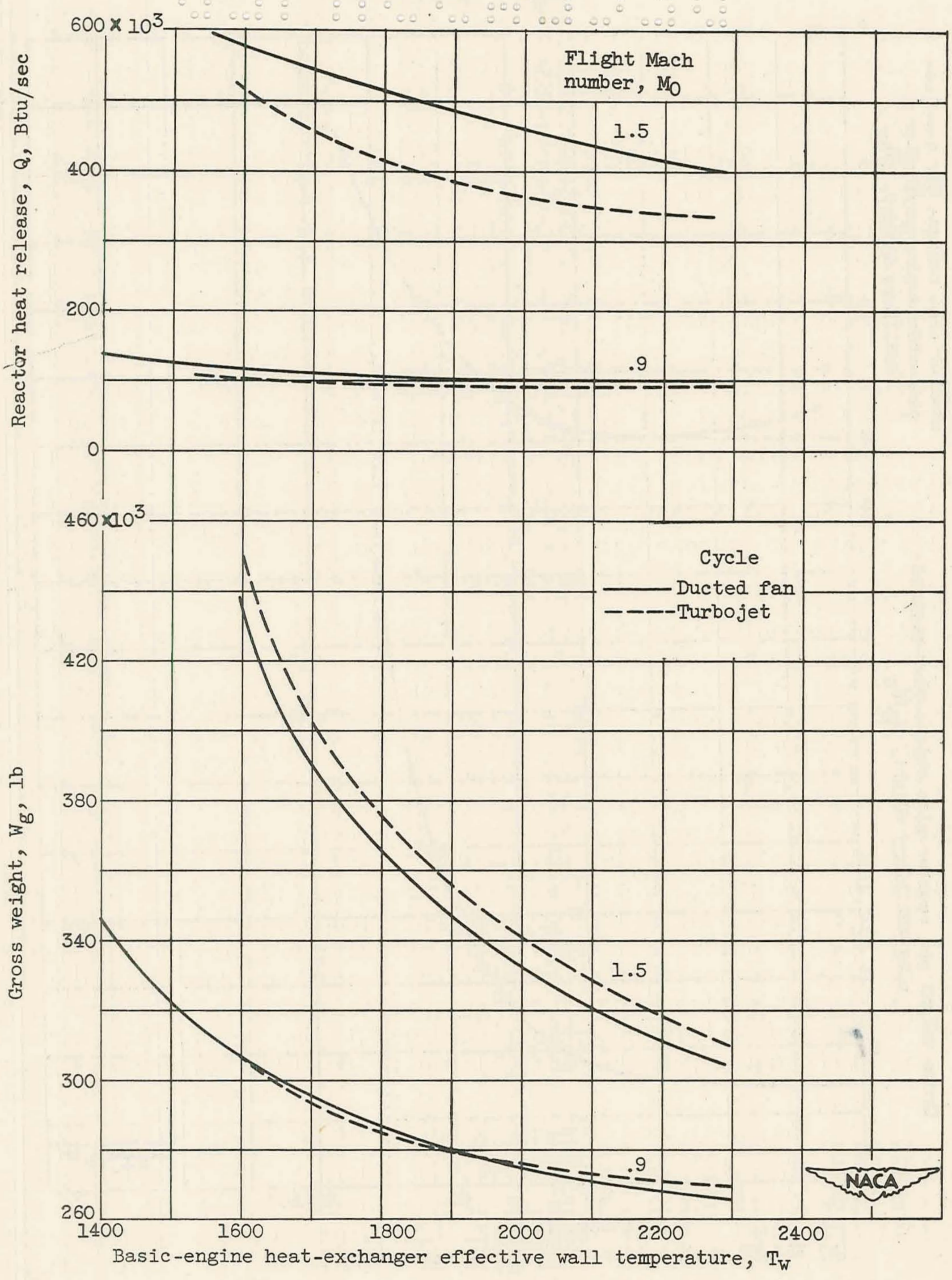

Figure 25. - Comparison of liquid-metal ducted-fan cycle with turbojet cycle. Structure-to-gross-weight ratio, 0.35; reactor-plus-shield-plus-payload-plus-auxiliary weight, 150,000 pounds; basic-engine and duct heat-exchanger effective wall temperature, 1800° R; optimum heat-exchanger inlet Mach numbers; optimum compressor pressure ratios; optimum fan pressure ratio; optimum duct-outlet air temperature.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

ANALYSIS OF A NUCLEAR-POWERED LIQUID-METAL DUCTED-FAN CYCLE

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